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Multi-Attribute Decision Making Analysis with Evolutionary Programming Applied to Large Scale Vehicle II

by

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SUBMITTED TO THE DEPARTMENT OF OCEAN ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

NAVAL ENGINEER
AND
MASTER OF SCIENCE IN OCEAN SYSTEMS MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Multi-Attribute Decision Making Analysis

with Evolutionary Programming

Applied to Large Scale Vehicle II

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Allan D. Andrew

Submitted to the Department of Ocean Engineering
on May 8, 1998 in partial fulfillment of the
requirements for the degrees of Naval Engineer and
Master of Science in Ocean Systems Management

Abstract

Ship and submarine design is a very complicated process that requires many trade-offs in design parameters in order to obtain the optimal vehicle effectiveness at the best cost. The number of potential designs is infinite, and the ship designer needs a tool to assist in searching this design space. This thesis uses an evolutionary program to determine the optimal designs of Large Scale Vehicle II, a one-quarter scale submarine model used for propulsor development. A set of designs is randomly generated and represented by binary strings. Each design is treated as an individual in a biological population and evaluated for total ownership cost and two measures of effectiveness. Measures of effectiveness obtained through expert opinion and computer modeling are explored. The designs with high effectiveness and low cost are chosen to produce offspring while the designs with poor effectiveness and high cost are removed from the population. Over many generations, the designs that yield high effectiveness dominate the population. No single design is identified as the optimum. Instead, the information is presented to the decision-maker on a two-dimensional plot that represents the frontier of all non-dominated designs. Each axis represents one of the measures of effectiveness and each level of cost is plotted on a separate curve. This process allows the decision-maker to choose one or several of the non-dominated designs to continue through feasibility and detailed design.

Thesis Supervisor: Alan J. Brown
Title: Senior Lecturer Naval Architecture and Marine Engineering

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My sincere gratitude goes to LCDR Mark Thomas, who took the time to help me understand genetic algorithms and their potential application to the design of submarines. This thesis relies heavily upon the work he has done in pursuit of his Ph.D. at MIT.

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Most of all I wish to thank my loving wife. The support she has given me over our entire life together, especially over the past three years, means more to me than anyone can know. She is a wonderful wife and mother. I know our one-year-old son, Harrison, can have no better care. What she does with him makes anything that I may accomplish pale in comparison. To Stephanie, all my love, forever and always.

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List of Symbols and Abbreviations

A1	Newport News LSV II baseline design
AHP	Analytical Hierarchy Process
ARD	Acoustic Research Detachment
ASSET	Advanced Surface Ship Evaluation Tool
ASW	Anti-submarine warfare
CAIV	Cost as an independent variable
C_d	Coefficient of drag
CER	Cost estimating relationship
C_f	Frictional resistance coefficient
CMOE	Combined Measure of Effectiveness
CNA	Center for Naval Analysis
COEA	Cost and Operational Effectiveness
C_r	Residual resistance coefficient
CVX	Next generation aircraft carrier
D	Maximum hull diameter
D_{aft}	Diameter of aft body
D_{fwd}	Diameter of the forward body
DIA	Defense Intelligence Agency
D_{mid}	Diameter of parallel mid-body
DTOC	Discounted total ownership cost
E	Sonar expected uncertainty band (dB)
EHP	Effective horsepower
ECM	Electronic counter measures
HAMOE	Hydroacoustic measure of effectiveness
HD/F CMOE	Hydrodynamic and flexibility combined measure of effectiveness
IRAD	Independent Research and Development
kWe	Kilowatt electric
L	Vehicle length (feet)
L/D	Length to diameter ratio
L_{aft}	Length of aft body
LCC	Life cycle cost
LCG	Longitudinal center of gravity
L_{fwd}	Length of the forward body
L_{mid}	Length of parallel mid-body
L_{pmb}	Length of parallel mid- body
LSV	Large Scale Vehicle
MAIE	Multi-attribute iso-effectiveness
MAU	Multi-attribute Utility
MBT	Main ballast tank
MOE	Measure of effectiveness
MOP	Measure of Performance
N_a	Shape factor aft

NAVSEA	Naval Sea Systems Command
N_f	Shape factor forward
NIS	Naval Intelligence Service
NSSN	New Attack Submarine
NSWC	Naval Surface Warfare Center
NUWC	Naval Undersea Warfare Center
OSD	Office of the Secretary of Defense
Rn	Reynold's number
SHP	Shaft horsepower
SHT	Special hull treatment
T_{cot}	Hull coating thickness (inches)
u	Kinematic viscosity (ft^2/sec)
V	Speed of interest for hydroacoustic trial (15 kts)
VCG	Vertical center of gravity
V_{Fr}	Froude scale maximum speed
V_k	Vehicle speed (knots)
V_{MAX}	Maximum speed of hydroacoustic run
V_{MIN}	Minimum speed of hydroacoustic run (18.5 kts)
x_{aft}	Position on aft body
x_{fwd}	Position on the forward body

1
Introduction

1.1 Background

The design of any complicated system is difficult because of the many trade-offs required between cost and effectiveness. For example, in the automobile industry, vehicle performance in terms of mileage and acceleration can be improved with the use of lighter aluminum or polymer composite parts instead of steel. Most manufactures use steel, however, because of the relatively low cost of steel fabrication. It is significantly less expensive to produce steel cars, and most consumers are currently not willing pay the premium for the increased performance.

Trade-offs must also be made between different measures of effectiveness. In general, lower weight automobiles have better fuel economy and acceleration, but have worse performance in crash-worthiness. Often government regulations can pit different measures of effectiveness against each other. The Federal Motor Vehicle Safety Standards dictate minimum crash-worthiness while the Environmental Protection Agency emissions regulations dictate minimum fuel economy. The designer is left to develop a balanced design that meets all requirements and provides vehicle performance at a price the consumer is willing to pay while maximizing profit for the company. [1]

There are many examples of complicated design problems that have an infinite number of possible options. Designers need tools that allow a structured search of the design space with automatic evaluations of effectiveness and cost to determine the best designs.

The problem is even more complicated if there are multiple objective attributes, especially if they have no numeric value associated with them. An objective attribute is any parameter that is optimized in a design problem. The only objective attribute for the automobile manufacturer is some measure of profit as a return on investment. To obtain an estimate of profit, however, the manufacturer must predict how many vehicles will be sold. This is by no means an easy task, but clearly, the number of vehicles sold depends upon the vehicle's perceived effectiveness and cost. Effectiveness depends upon safety, cargo carrying capability, comfort, overall vehicle attractiveness, etc. Cost to the consumer depends on purchase price, fuel cost, maintenance cost, resale value, etc. To further complicate the problem, each of the high level measures of effectiveness depends upon many lower level measures of effectiveness or measures of performance. For example, comfort depends upon NVH (noise, vibration and harshness), legroom, headroom, quality of seats, steering wheel adjustments, etc.

To solve the design issues of design space search and difficult-to-compare measures of effectiveness, this thesis proposes the use of an evolutionary program with expert opinion to develop a complete set of non-dominated designs, or Pareto frontier. A design is non-dominated if no other possible design performs better in all objective attributes. Expert opinion is used to combine the many measures of effectiveness into several combined measures of effectiveness. This allows combination of similar items that can more easily be compared by the decision-maker. Two methods of obtaining expert opinion are explored: Analytical Hierarchy Process (AHP) and Multi-Attribute Iso-effectiveness (MAIE).

1.2 Evolutionary Programs

The evolutionary program allows an effective search of the potential design space. The expert opinion determines what constitutes a good design and the evolutionary program searches the design space to determine which potential designs attain those objectives. The evolutionary program is based on the principles of heredity and evolution found in nature. A population of individual designs is randomly chosen and represented in a binary string called a chromosome. Each individual in the population is evaluated for its objective attributes (i.e., measures of effectiveness and cost). A new population is formed by selecting the more fit individuals for reproduction to produce children. Random mutations occur in the process to simulate mutations that occur in nature [2]. Individuals with poor objective attributes are chosen for removal from the population. Over many generations, the program converges to a set of designs that represents the non-dominated frontier of designs. If the true non-dominated (or Pareto) frontier is found, then there is no design that has a better objective attribute without another objective attribute having a worse value. [3]

1.3 Large Scale Vehicle II

The method proposed in this thesis is applied to Large Scale Vehicle II (LSV II), "an advanced, autonomous," large-scale submarine model "which will provide a platform for fundamental research and development". LSV II will operate at the Acoustic Research Detachment facility at Lake Pend Oreille, Idaho and "provide a platform for evaluating new technologies for improvements in acoustics, propulsion, and hydrodynamics". [4]

LSV I, currently operating at the Acoustic Research Detachment Facility, was constructed to evaluate the propulsor on USS Seawolf (SSN-21). Several different propulsor designs were evaluated before the selection of the final variant was chosen. LSV I will remain operational until LSV II is completed. Consideration was given to upgrading LSV I with an improved sensor system and hull coating, but was rejected because of lack of arrangeable volume available for a trim tank. LSV I does not currently have hull coating and has only small trim tanks. Because the coating compresses as the vehicle dives, large trim tanks are required and LSV I does not have enough volume margin to add the required tanks. [5]

Other than the hull coating, the biggest difference between LSV I and II is the requirement for LSV II to support hydrodynamic testing. No hydrodynamic testing is conducted with LSV I. [5]

The evaluation of fitness of each LSV II includes two measures of effectiveness and one measure of cost. The hydroacoustic measure of effectiveness (HAMOE) is a single calculated value that represents expected uncertainty in acoustic measurement. The hydrodynamic and flexibility combined measure of effectiveness (HD/F CMOE) is an expert opinion combination of three measures of performance. Discounted Total Ownership Cost (DTOC) is used as the measure of vehicle cost.

LSV II is used as a platform for application of the proposed method because it is a simplified design, yet representative of a full-scale ship or submarine design problem. There is only one internal level on the vehicle, so the arrangement problem is simplified to a linear stack of the required components. There are no crew members on board so there is no human support problem. The detailed design problem of control of an

autonomous vehicle is more difficult. For the concept design of this analysis, however, it is assumed that the control system is similar for all vehicles, carrying the same cost and similar performance.

Naval ships and submarines are among the most complex systems ever designed. A tool that assists the designer in determining the Pareto frontier would be of great value. It is proposed that the method used in this thesis can be extended to the more complex design problem of a full-scale ship or submarine with only minor changes.

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2
Previous and Current Methods for Concept Ship Design

A study is made of the methods used for concept ship design for the New Attack Submarine (NSSN), next generation aircraft carrier (CVX) and the design method for LSV II.

2.1 NSSN

Concept level design decisions for the New Attack Submarine were made in a two phase Cost and Operational Effectiveness Analysis (COEA). The first phase was completed in July of 1993 and the second phase was completed in May of 1995. [6,7]

2.1.1 COEA Phase I

Phase I of the COEA was conducted by the Center for Naval Analysis (CNA) with technical assistance from Naval Sea Systems Command (NAVSEA) for design information and cost estimates. All designs were conducted using a parametric characteristic analysis. Cost was evaluated with a parametric analysis of life cycle cost using a discount rate of 4.5%. Within Phase I, two separate analyses were conducted. The goal of the first part of Phase I was to narrow the focus from 12 initial designs to a smaller number of designs for further evaluation. Each of the 12 designs was evaluated in 3 different scenarios at a rough order of magnitude. The scenarios were initially dictated in general terms, from which Naval Intelligence Service (NIS) generated the order of battle.[1] Naval Surface Warfare Center (NSWC) evaluated minefield penetration

[1] Order of battle is a detailed description of opponents' forces including ships, submarines, aircraft, troops, etc.

ability, and Naval Undersea Warfare Center (NUWC) used SIM II[2] to evaluate search effectiveness and exchange ratio in combat against a variety of opponents. The performance of each design was graded in each scenario to obtain a mission analysis score and force on force analysis score. In the terminology of this paper, these are measures of effectiveness. The scores were plotted versus cost to analyze cost-effectiveness. [6]

The first part of Phase I concluded that there are 3 design discriminants that dictate submarine effectiveness. Design discriminants are inherent ship characteristics that have a large impact on effectiveness and cannot be easily changed after the ship is constructed. The three design discriminants are stealth, speed and payload. In the terminology of this paper, design discriminants are referred to as measures of performance. It was decided that 4 of the 12 designs met the required design discriminants at acceptable cost and were carried forward to the second part of Phase I. [6]

During the second part of Phase I, a more detailed analysis was conducted for the 4 best designs. The same 3 scenarios were used, but more data was collected on the performance of each variant in order to determine which of the 4 final selections would be carried forward for more design work. At the end of the second part of Phase I, the winning design was the nuclear attack submarine with "Seawolf-like" quieting, 28+ knots of speed, four 21 inch torpedo tubes and 12 vertical launch cells. [6]

---

[2] SIM II is a Monte Carlo based engagement model that predicts the performance of proposed submarines in various war scenarios.

Results from Phase I of the COEA were met with some criticism. Some members of the Defense Intelligence Agency (DIA) thought that the wrong scenarios had been used and that the order of battle for the enemy was incorrect. Similarly, individuals in the Office of the Secretary of Defense (OSD) thought that more submarine variants should have been evaluated. Since DIA and OSD had an official role in reviewing the COEA results, this presented a major problem for the program office. [8]

2.1.2 COEA Phase II

A second COEA was commissioned to study the effects of varying design parameters from the baseline design found in Phase I. From the beginning of Phase II, all of the reviewers and decision makers were invited and encouraged to be involved in the process as full members of the COEA team. Consensus was obtained in the scope and assumptions of the study, including variant options, scenarios and orders of battle. Obtaining consensus on the scope of Phase II of COEA was not easy, but the process gave all people involved an investment in the analysis that yielded more credibility in the results. [8]

The baseline ship for all variants was a nuclear attack submarine with Seawolf-like stealth, 25,000 SHP, 28+ knots, 7500 tons submerged displacement, four 21-inch torpedo tubes and 12 vertical launch cells. From this baseline a sensitivity analysis was conducted by adding each of the following items and the evaluating effects on the major warfare areas:

Light Weight Wide Aperture Array (LWWAA)
Vertical Launch Cells (0, 4, 8, 12, 20)
Special Hull Treatment (SHT)
Chin Sonar Array
Lock Out Chamber (3, 6, and 9 team size)

Two types of towed arrays
3" and 6.25" Counter Measures

Measures of effectiveness were selected to evaluate each platform's war-fighting performance in the 7 mission areas:

Covert strike
Anti-submarine warfare
Covert intelligence collection
Anti-surface warfare
Special warfare
Mine warfare
Battle group support

Each variant was placed in an operational context with a defined threat and environment. The scenario was then executed and the MOE in each war-fighting area determined. Measures of effectiveness in each war-fighting area were plotted as a function of cost. The decision-maker was presented with these graphs in order to make a final decision on the final variant. [7]

The COEA process was able to find the best variant in the design space that was evaluated, but the design space that was compared was very small. Phase I of the COEA looked at only 12 different variants and the Phase II looked at relatively small changes around the variant determined to be best from Phase I. There is no guarantee that the final variant found is the best of all possible in the design space. Hopefully, the designers working on the project were able to design a submarine with effectiveness that is near the optimum. A design tool that could assist with this process is needed.

2.2 CVX

Concept studies for the next generation of aircraft carrier were started in 1996 and are planned to be completed by 2000. The CVX team is using a multi-step decision process similar to the two phase COEA for NSSN. Unlike New Attack Submarine,

however, CVX plans to conduct more analysis separate from the congressionally mandated studies. [9]

The COEA has been replaced by an Analysis of Alternatives (AOA) for CVX. Essentially the purpose of the AOA is identical to that of the COEA, using a different name. Phase I of the AOA, completed in 1997, was designed to select the size and composition of the airwing. This study was similar in design and execution to Phase I of the New Attack COEA. Parametric carrier designs were evaluated in combat scenarios to determine effectiveness. Airwing size and composition were varied and the design was balanced using the Navy's computer program for parametric design, ASSET (Advanced Surface Ship Evaluation Tool). The designs were then evaluated for effectiveness in war scenarios as a function of airwing size and composition. The decision was made to proceed with an airwing with between 60 and 80 aircraft because of the increased strike performance of the larger airwings. OSD had concerns about the study methods and reduced the minimum airwing size to 50 aircraft. [9]

The remaining portions of the concept design process focus on maximizing the "-ilities." These can be thought of as groups of measures of effectiveness and measures of performance (MOEs and MOPs). There are 8 "ilities":

Combatability
Survivability
Sustainabiltiy
Interoperability
Flexibility
Supportability
Mobility
Affordability

The CVX design team assumes these "ilities" to be independent of each other to a first order of magnitude. Affordability (low cost) is assumed the most significant driver of the problem and is directly related to all of the other "ilities". [9]

The CVX team is currently in the process of defining MOEs and MOPs that can be used to quantify each of the "ilities". The desire is to quantify effectiveness at four different levels: campaign, mission, engagement and engineering. The campaign level has 5 sub-levels ranging from pre-deployment through sustained combat. Each sub-level has quantitative MOEs associated with it. For example, the proposed MOE for sustained combat is target attrition. At the mission level, the performance of the carrier in a specific mission area is evaluated. The mission areas include strike, anti-air warfare, anti-surface warfare, anti-submarine warfare, self-defense, etc. At the engagement level, different methods of employment are compared. At the engineering level, specific systems are compared. In the mission area of self-defense, active and passive self-defense measures are traded. At the engagement level under self-defense, active chaff can be compared to active ECM (Electronic Counter Measures). And at the engineering level under self-defense, different active ECM systems using different frequency bands can be compared. [9]

Four levels are used because decision-makers at different levels within the design team have different requirements for information. The engineering team working on the design of the active ECM system may need to only have information comparing different types of ECM performance. OSD, however, is primarily concerned with integration of the new carrier into national defense at a very high level, and would be mostly interested in the campaign level. [9]

The information for each level or sub-level is presented on a four-dimensional plot. Each of the three axes represents one of the MOEs at this level, and the fourth dimension is represented by color shading on the plot and represents affordability (cost). The options that give the best cost-effectiveness at each level are passed to the next higher level for further evaluation. [9]

Ultimately, MOEs as measured in required mission scenarios, cost and risk are the critical objective attributes. MOPs determine MOEs, and design parameters determine MOPs, cost and risk. MOPs and design parameters are not objectives unto themselves. [13] Although the CVX design team confuses these basic concepts, at least it attempts to quantify all aspects of the problem in order to make a definitive cost-effective decision.

2.3 LSV II

The Large Scale Vehicle II (LSV II) was proposed as a replacement for LSV I to continue propulsor acoustic evaluation and research. LSV II is also being designed to conduct hydrodynamic research. The program is under severe acquisition cost limitations and is using cost as an independent variable (CAIV) to maintain costs within budget. Since LSV II will be a one-of-a-kind vehicle, engineering costs cannot be spread over the cost of several vehicle purchases. Maintaining engineering costs as low as practicable is an even larger concern than on most acquisition projects. For this reason, as much as possible, design work from LSV I is being used for LSV II. This initially led to the decision to build the hull to the same specifications as LSV I, a Seawolf geo-similitude model. When additional funds were budgeted for LSV II, the decision was made to reconsider New Attack geo-similitude, since acoustic information on Seawolf had already

been gathered with LSV I. Very little study was given to any other geo-sim because of the cost constraints on the program. The Seawolf geo-sim was under consideration for maximum cost savings to the LSV program. The New Attack geo-sim was chosen because additional funding was authorized specifically to build a New Attack geo-sim to save model-testing costs for New Attack. [5]

Another major cost constraint on the program was the choice of the propulsion motor. In order to meet the budget, the motor selected was the Electric Boat Radial Gap Permanent Magnet Motor that was developed under Electric Boat's Independent Research and Development (IRAD) program. [4]

Because of the various constraints placed on the LSV design by forces outside of the program, it is difficult to compare the LSV concept design process to other methods.

2.4 Comparison with Proposed Method

The concept design decision tools used by NSSN and CVX both have several similarities with the method proposed in this thesis. In all of the methods, a design is evaluated for cost and effectiveness, and the designs are compared to find the optimal solution for the final design. The important item missing from both previous methods is a structured method to search design space to ensure that the decision-maker is selecting from among the over-all non-dominated designs. Evolutionary programs can provide this structure.

3

General Process

3.1 Overview

Designing a ship is very a complicated and involved process with a very large number of interrelated design parameters. All design processes attempt to determine which of the possible combinations are the best. The major hurdles to overcome in any multi-objective design process are:

1. Selection of design parameters.
2. Determination of objective attributes (effectiveness and cost).
3. Selection of the best designs (those not dominated by other designs).
4. Final selection from among the non-dominated designs.

The determination of design effectiveness and cost can be very computationally intensive and has traditionally required significant involvement of the ship designer. Because each design has required such a significant amount of effort, only a small fraction of the possible designs have traditionally been evaluated. This thesis proposes automating the design process so that a computer model can evaluate designs from selection of design parameters through determination of the non-dominated designs. The designs to be evaluated are chosen through the use of an evolutionary program that treats a group of designs as a biological population that evolves to the best possible designs. The designs with the best objective attributes are chosen to reproduce, while the ones with the worst objective attributes are removed from the population. The non-dominated

frontier can be defined using this method by evaluating only a fraction of all possible designs.

3.2 Design Parameters

Design parameters are those physical characteristics of the proposed solution that are varied in an attempt to obtain the best effectiveness at the least cost. They are the smallest building block in concept ship design. Design parameters are grouped to form potential designs. The designs are then balanced and evaluated for feasibility. Design parameters include such characteristics as size, shape, material, subsystems, equipment, etc. Most design parameters have competing effects on the overall effectiveness of a final design. For example, in Large Scale Vehicle, adding hull coating lowers the acoustic signature of the vehicle, but it also reduces the vehicle maximum speed and increases cost. Maximum speed is lowered for two reasons:

1. Drag is increased due to more wetted surface area.
2. The trim tank must be sized to compensate for compression of the hull coating. A larger trim tank uses internal volume that could otherwise be used for more battery cells.

Without analyzing a wide range of coating thickness it is extremely difficult, if not impossible, to determine the optimum thickness. The total impact of each design parameter on the ship design must be evaluated.

When combined with all of the other design parameters, the number of possible designs grows exponentially. Even with a simplified design analysis of LSV II using only 8 design parameters, the number of possible designs is in the millions. With a full-

scale ship design, the number of possible combinations can easily number in the billions or trillions.

3.3 Effectiveness and Cost

Many potential combinations of design parameters are not feasible for a number of reasons: instability, lack of volume or area balance, lack of weight balance, etc. Of the feasible designs, only a small fraction are non-dominated. A design is dominated if another design performs at least equally well in all objective attributes and better in at least one. For example, it does not make sense to choose a design with a higher cost if all of the measures of effectiveness are the same.

Each set of design parameters maps to a set of objective attributes which defines the non-dominated or Pareto frontier. This frontier can be plotted in two or more dimensions for assessment by the decision-maker. (See Figure 3-1.) In theory, the number of objective attributes that can be compared in the Pareto frontier is not limited. In practice, however, limiting the number of objective attributes to 3 or 4 simplifies presentation of the information to the decision-maker. Any more than 3 or 4 is very difficult to evaluate. In this thesis, the number of decision variables is limited to 3:

1. Discounted Total Ownership Cost
2. Hydroacoustic Measure of Effectiveness
3. Hydrodynamic/Flexibility Combined Measure of Effectiveness

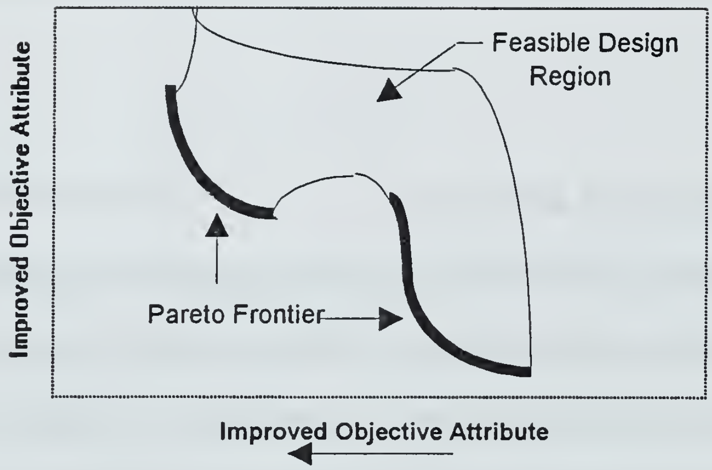

Figure 3-1 Pareto Frontier and Feasible Design Region for 2 Objective Attributes

With 3 objective attributes, the results can be plotted on a 2 dimensional graph with different curves representing different costs. If 4 objective attributes are used, the frontier can be plotted on a 3 dimensional graph with different colors representing different costs. More variables can very quickly overwhelm the decision-maker, however, making the results very difficult to interpret.

Selection of objective attributes is a difficult step in the decision making process. In nearly all cases, cost is one of the objective attributes, and the other objective attributes are measures of effectiveness.

3.3.1 Cost

There are several possible costs that could be used in this decision analysis. Acquisition cost is often used because it is usually the largest single cost in a program and has significant political consequences. It is often thought that if the initial purchase price can be funded, then the operational costs in the future will be funded because the

yearly operating and support expenditures are usually much smaller than the acquisition cost and are funded from different sources. Over the life of the ship, however, these operating and support costs typically sum to more money than the initial investment cost, even when analyzed on a discounted basis.

Another potential cost is life cycle cost. Life cycle cost (LCC) is typically defined as the sum of acquisition cost and direct operational and support cost over the life of the program. Operating and support costs include direct expenditures for energy consumption, manning, upgrades and maintenance. Indirect costs are not usually included in life cycle costs. For example, the cost of paying the salary of the maintenance workers is included, but the cost of any schooling required to train the maintenance workers is not.

When all indirect costs are added to life cycle cost, total ownership cost (TOC) is obtained. Total ownership cost can be very difficult to calculate because of the uncertainty in how far it is appropriate to extend the indirect costs and the potential to double count costs between programs. The effort expended in obtaining a correct cost estimate is important, however, in properly defining the Pareto frontier.

A problem is encountered when using a TOC that is not discounted. In the non-discounted case, a dollar spent in the first year is treated the same as a dollar spent at the end of life. Since money has a time value associated with it, money spent in future years should be discounted at an appropriate rate to present value. For this reason it is important to use discounted TOC (DTOC). The Office of Management and Budget sets the discount rate for the federal government. The discount rate for "public investment and regulatory analyses" is currently set at 7%. Systems for the Department of Defense are

usually evaluated under "cost-effectiveness analysis", with a discount rate equal to the real interest rates on Treasury Notes with a maturity equal to the period of concern. The 20-year discount rate is currently 3.7%. [10] Discount rates in the 1980's were set at 10%. This thesis uses a compromise discount rate of 6.0%.

Selection of the proper discount rate is extremely difficult, but also very important. High discount rates discourage yearly expenditures and reward early savings, while low discount rates encourage expenditures early in the program and reward savings late in the program.

3.3.2 Measures of Effectiveness

Measures of effectiveness (MOEs) are functional metrics of a design relative to a specific scenario. Measures of performance (MOPs) are functional metrics that have an impact on the MOEs, but are not scenario dependent and are not the end result. [11] For example, in the design of a warship, maximum speed is a MOP that is an input to a MOE such as how many submarines the warship can sink. Having a high maximum speed allows the ship to transit to the war zone more quickly allowing more effectiveness in anti-submarine warfare and sinking of more submarines. The maximum speed is an important factor, but it does not indicate directly how effective the platform is. To determine effectiveness, the ship must be placed in a scenario. Evaluating MOPs requires engineering models. Evaluating MOEs requires warfighting models.

As much as practical, the MOEs should be metrics that can be predicted using computer models. In the anti-submarine warship example, war-game computer simulation could be used to obtain the MOE metric. Perhaps exchange ratio (number of

submarines sunk to number of friendly ships lost) over an extended campaign, or series of campaigns, is the desired MOE. For this thesis, one of the MOEs used is hyrdroacoustic effectiveness, which depends upon the MOPs of vehicle speed and vehicle endurance. The MOE also depends on the design parameters of hull coating thickness and facility sonar type, which dictate acoustic performance of the system. The output from the MOE is a calculated number that represents the expected uncertainty in prediction of the propulsor acoustic performance of the vehicle. A smaller hydroacoustic MOE indicates better effectiveness in this area.

3.3.3 Combined Measure of Effectiveness (CMOE)

A single number cannot always be chosen to reflect the effectiveness of a design in a certain area. In the case of the anti-submarine example, perhaps it is important to have separate numbers for deep water and littoral effectiveness. One option is to create another category for comparison on the Pareto frontier. If the number of objective attributes grows to more than 3 or 4, however, presenting the decision-maker with the information becomes a problem. Another option is to use expert opinion to group 2 or more MOEs into a combined measure of effectiveness (CMOE).

3.3.3.1 Previous CMOE Methods

Whitcomb [12] outlines several different methods to obtain this CMOE:

1. Weighted Sum

2. Hierarchical Weighted Sum

3. Analytic Hierarchy Process (AHP)

4. Multi-attribute Utility (MAU) Analysis

All of the methods used to obtain a CMOE have the first two steps in common. The first step is to determine the attributes to be combined (MOEs or MOPs) to obtain the CMOE. The next step is to establish goals and thresholds. Goals represent the best value the decision-maker believes to be obtainable with the technology available in the time frame of the project, or the value at which further improvement no longer adds significant benefit to the project. The threshold represents the value of worst acceptable performance. Below this value, it is considered not worth continuing the project. [13]

The weighted sum method is the simplest of these methods. The CMOE is obtained by summing the product of the MOEs and their respective weightings. The MOEs are weighted by the decision-maker according to the MOEs perceived importance. This method has the advantage of simplicity, but its validity is highly dependent on a clear and precise definition of the problem and a thorough understanding of this definition by the expert. [14]

Hierarchical weighted sum is an extension of the weighted sum method with a more structured approach to the problem. The top of the hierarchy is the CMOE. Below this are the top-level measures of effectiveness. In the warship example, the top level MOE is anti-submarine warfare. Below this are lower level MOEs, which in the example are deep water ASW and littoral ASW. If the lowest level MOE cannot be numerically evaluated, then the hierarchy can be broken down further into MOPs. For example, ASW weapons, maximum speed, endurance, etc. all affect the ability for a warship to succeed in an ASW mission. This method also uses expert opinion to obtain the relative weightings of each level of the hierarchy, but complex problems are more easily handled

in the hierarchy structure, allowing the design team and the decision maker a format to facilitate discussion. This method also has the benefit of simple implementation on any spreadsheet program.

The Analytical Hierarchy Process (AHP) uses a hierarchy similar to the one used for hierarchical weighted sum, but relies on the decision maker to make pairwise comparisons as to the relative importance of each item within a level of the hierarchy. The relative weightings for each comparison are then placed in a square matrix with row and columns representing the elements of each sub-objective in the hierarchy. The weights for each objective are the numbers within the eigenvector associated with the largest eigenvalue. AHP is not as simple to implement as the first two methods, but with the use of "Expert Choice" software [15], the process is fairly straightforward. The number of elements compared at each node should typically be limited to no more than 7 to facilitate the decision makers ease of comparison. This is typically not a significant problem; more branches can be added to the hierarchy if necessary.

Multi-attribute utility analysis involves obtaining the decision-maker's preference or utility for certain levels of performance or effectiveness. A hierarchy is not required for this method, but may be useful in formulation of the problem. Utility functions, if generated properly, provide insight into the decision makers preferences for effectiveness, performance, uncertainty and risk. The biggest drawback to the use of MAU analysis is the difficulty in obtaining utility curves. The decision-maker is asked questions dealing with the probability of certain outcomes of the designs. Decision-makers are often not experienced with thinking about the probability of outcomes, and experienced consultants are required to assist in creation of the utility curves. Another

drawback of the method is that the results are not obtained from the interviews directly, but through a somewhat indirect mathematical method. The final utility curves can often be non-intuitive, which can cause problems in group facilitation if there is more than one decision-maker.

3.3.3.2 Multi-Attribute Iso-effectiveness(MAIE)

A new method for achieving a CMOE is proposed in this thesis: Multi-Attribute Iso-Effectiveness (MAIE). This method is an attempt to combine the direct questioning of AHP and weighted sums with the inherent ability to assess risk tolerance of MAU. The basic premise for the method is this: ask the decision-maker to provide the combinations of MOEs that give equal value. If these curves are then plotted, iso-effectiveness curves are obtained. (See Figure 3-2) The major drawback of this method is that it is extremely question intensive and cannot be used to combine more than 3 or 4 attributes. The method also has no proven record.

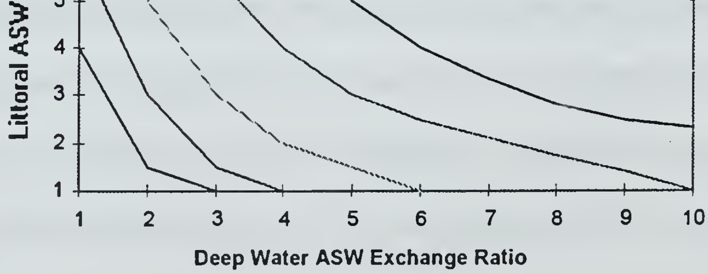

Figure 3-2 Example Iso-effectiveness Curves

3.3.3.2.1 Administering MAIE Surveys

Like the previous methods, goals and thresholds must be established for the characteristics to be combined. After the goals and thresholds have been established, a questionnaire for the decision-maker is framed. Assume the 2 dimensional example of combining deep water ASW and littoral ASW is to be used and the goal for each is an exchange ratio of 10 and the threshold for each is an exchange ratio of 1. The decision maker is then presented with the following question: "If design 'A' has a deep water exchange ratio of 5 and a littoral exchange ratio of 5, and design 'B' has a deep water exchange ratio of 7, what value of littoral exchange ratio for design 'B' gives the two designs equal value?" Since higher exchange ratio is always better, the answer to the question must be between 1 and 5. The answer cannot be less than 1, because then it is below the threshold and design "A" has more effectiveness. The answer cannot be greater than 5, because then design "B" is better in both categories and would have more value than design "A". This gives the decision-maker an initial bracket for the answer. An effective approach is to continue the bracketing procedure. For example a littoral exchange ratio of 4 might be better, but an exchange ratio of 2 might not. A reasonable answer from the decision-maker might be that the equivalent value occurs for an exchange ratio of 3. (See Figure 3-2)

Next the decision maker is asked to compare the above two designs ("A" and "B") with a third design "C" that has a deep water exchange ratio of 3. Again the initial bracket can be made that the answer should be between 5 and 10. The answer cannot be above 10 because that is the goal set for problem and it is assumed that there are no

solutions above this value. The answer cannot be less than 5, because if it were, then design "A" would be better in both categories and have a higher value. Again the bracketing procedure can be performed and a reasonable answer might be 7. The deep water ASW exchange ratios are varied until the entire iso-effectiveness line is obtained.

The questions then start over to define another iso-effectiveness line. For example, the first design on the next iso-effectiveness curve might have both exchange ratios equal to 3. The process is repeated until the entire grid is populated with iso-effectiveness curves.

The slopes of these curves represent the relative value of deep water ASW to littoral ASW. In regions where the slope is near 1, deep water and littoral ASW have close to the same value. In regions where the curves are very steep, deep water ASW is more valuable. In regions where the curves are very flat, littoral ASW is more important.

To extend the method to a third dimension, the assumption is made that the iso-effectiveness curves obtained for two dimensions are not dependent upon the third dimension. The decision-maker is told to hold the third variable constant while developing the iso-effectiveness curves for the first two. Another set of iso-effectiveness curves is then obtained for the third variable and one of the first two variables. These two sets of iso-effectiveness curves are then combined to form iso-effectiveness surfaces. Cross sections of these surfaces perpendicular to one of the variable axis yield iso-effectiveness curves of the remaining two variables.

In theory, this process can be extended to more dimensions, but the number of questions required to obtain the iso-effectiveness curves increases rapidly with increasing

numbers of variables. If the number of points required to find a 2-dimension iso-effectiveness curve is P (typically between 10 and 30) and the number of variables is N, then the total number of points that must be evaluated is:

$$\text{Number of Points} = P * (N-1)$$

3.3.3.2.2 Interpreting MAIE Surveys

The CMOE for a set of objective attributes described by an iso-effectiveness curve (surface) is the intersection of the iso-effectiveness curve (surface) of the attributes under consideration with the vertical axis. The CMOE for the 2 dimensional example is the value of the independent variable at the location of the threshold value of the dependent variable along the iso-effectiveness curve on which the point of interest lies. For example, in Figure 3-1, if the deep-water exchange ratio is 5 and the littoral exchange ratio is 3, the point plots on an iso-effectiveness curve. When this iso-effectiveness curve is traced to the point where it crosses the threshold value for deep-water exchange ratio (1), the CMOE is found to be 9. If the deep-water exchange ratio is 5 and the littoral exchange ratio is 2.25, the point plots halfway between two iso-effectiveness lines. These two curves intersect the vertical axis at 7 and 9, so the CMOE is 8.

If the iso-effectiveness curve does not intersect the dependent variable axis, then the CMOE is obtained by extrapolating the iso-effectiveness curve to the dependent variable axis. Note that this yields a number greater than the goal for the dependent variable. The CMOE does not represent the actual value obtained in the independent variable space; it merely gives a relative value of the effectiveness of the combination of variables.

The process in 3 dimensions is similar, but instead of interpolating iso-effectiveness curves, iso-effectiveness surfaces are interpolated. The variable that is used to obtain both sets of iso-effectiveness curves is the independent variable that is used to express the CMOE. The CMOE is the value of the independent variable on the iso-effectiveness surface where the values of the dependent variables are equal to the threshold value. A specific example of the 3-dimension application to LSV is presented in Chapter 4.

3.4 Evolutionary Program

Once objective attribute functions or models are defined, the task remains to obtain the Pareto frontier: those designs that cannot be improved in one objective attribute without sacrificing another objective attribute. Of the large number of potential designs, only a small fraction are typically non-dominated. For simple designs, it may be possible to evaluate all of the possible combinations of design parameters and determine all of the non-dominated designs. For more complex design problems, however, the exhaustive search method is not feasible because it takes too long to complete the evaluation. Some sort of optimization program must be used to obtain the Pareto frontier. This thesis proposes the use of an evolutionary program.

3.4.1 Evolutionary Program Background

An evolutionary program treats an individual design as a member of a biological population. The members of the population with design parameters that map to the most dominant objective attributes are chosen to mate and produce offspring. The members of the population with dominated objective attributes are removed. After many generations

the genetics of the population improve, and the population approximates the Pareto frontier. The general flow-chart for an evolutionary program is presented in Figure 3-3.

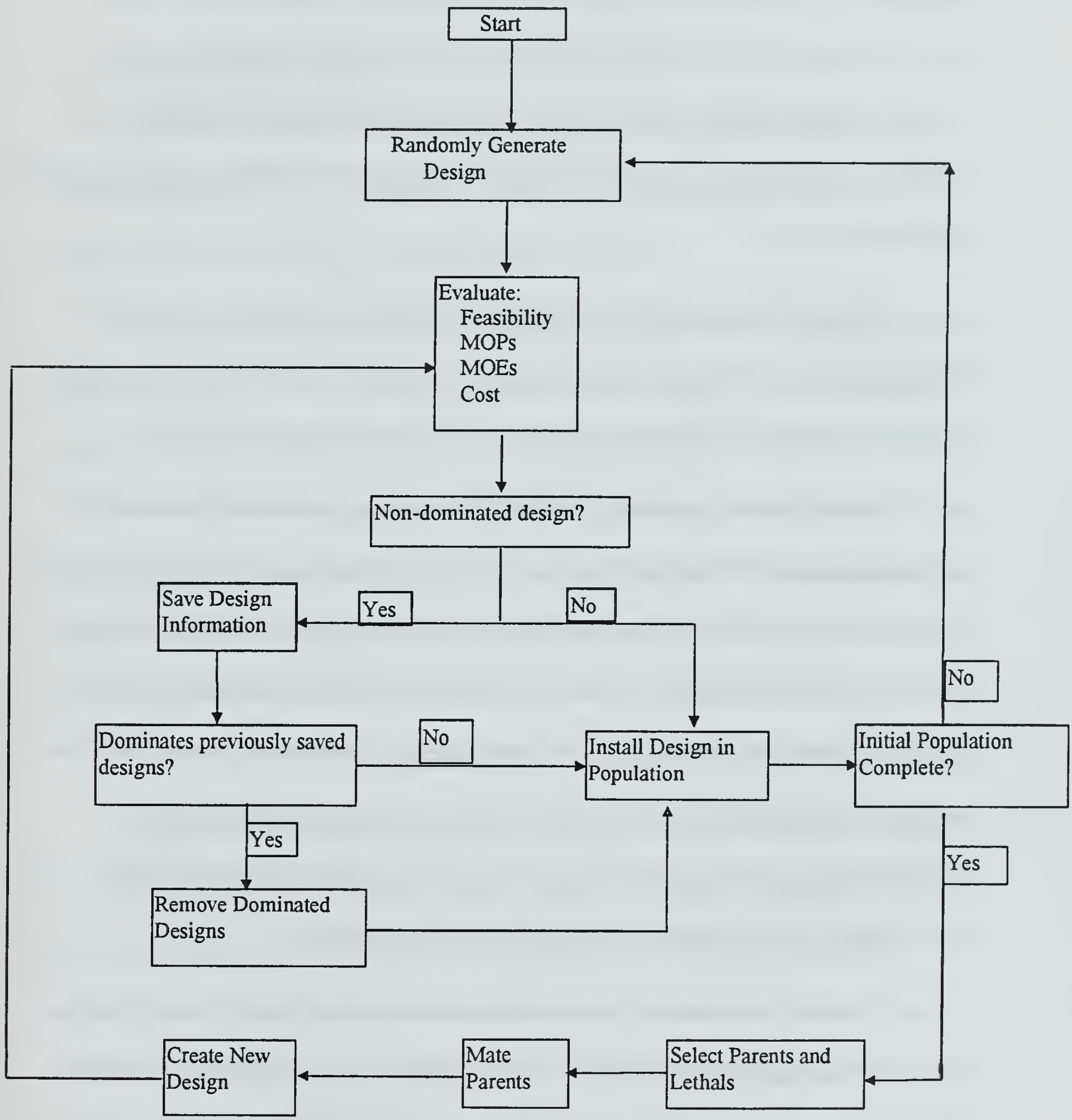

Figure 3-3 Flow Chart for Evolutionary Program

The theory behind evolutionary programs is currently uncertain and controversial. Experimental results indicate that the process shows promise in optimizing solutions, especially for "ill-behaved" problems when discontinuous or disjoint functions are present. There has been a significant amount of research about optimizing single objective attribute problems, but relatively little in the area of multi-objective attribute problems. Evolutionary programs to optimize Pareto frontier problems are even less well documented. [3]

Evolutionary programs have the advantage that they are simple to implement. They can readily be applied to many optimization problems in a straightforward method. The process is easy to understand because it is intuitive in its application. [3]

Another advantage of the method is that it provides a good combination of exploration and exploitation of the design space. Exploration ensures that no areas of the design space are ignored, while exploitation implies that solutions with good fitness are used to further increase fitness. Some other search methods can focus prematurely around local optimums found early in the search process, perhaps missing a global optimum. Evolutionary programs tend not to have this problem. They use the information that is contained in the genetics to exploit local optimums, while still exploring the entire search space, especially through mutations. [3]

A major disadvantage of an evolutionary program is the lack of formal proof about why the algorithm works. There is some research that suggests that for certain problems other types of search engines work better. Because of the lack of formal theory and mathematical proofs, the best method to set up an evolutionary program is not fully

understood. The best method seems to be to set up the problem, and then vary the evolutionary program parameters until the algorithm is operating effectively. [2,3]

3.4.2 Binary Representation

A binary string called a chromosome represents each potential design. The chromosome is composed of genes that represent individual design parameters. The genes can represent either discreet or continuous variables.

For discreet variables, it is advantageous to force the number of options for the variable to be of the form 2^N, where N represents the gene length. This simplifies the representation because each gene is a binary string that represents 2^N possible combinations. If the number of options for a discreet variable is not of the form 2^N, then 2 or more chromosomes can be combined to represent the variables. Alternatively, values of the gene can be made infeasible. If these values are generated in the evolutionary algorithm, then the design is not evaluated. This thesis uses 2 discreet variables: battery type, which has 4 options and sonar type, which has 2 options.

Continuous variables are represented in the binary strings as discreet variables. The separation between the variable values depends on the length of the gene chosen. A gene that has only one binary digit can represent only the minimum and maximum variable values. The total number of values that can be represented is 2 raised to the number of binary digits in the gene. The separation between the variable values is:

$$Separation = \frac{Value_{Max} - Value_{Min}}{2^{GeneLength} - 1}$$

It is important to ensure that the chromosomes are long enough to provide enough information so that large gaps are not created in the objective attribute space. However, it is also important not to make the gene too long, as each binary digit added to the chromosome doubles the number of possible designs. A good approach is to start with chromosomes slightly shorter than desired, and then, after the genetic algorithm is operating correctly, increase the size of the chromosomes until the desired precision is reached.

3.4.3 First Generation

The first generation of potential designs is created randomly. Each element of the binary chromosome string is randomly assigned a value of "0" or "1". After the entire chromosome has been generated, the design is decoded into a base-10 representation and evaluated for feasibility, performance, effectiveness and cost. The process is repeated until the first generation is fully populated.

The optimal size for the generation depends upon the individual design problem. A larger population allows more genetic information to be available to the algorithm at any given time, but a larger population also takes longer to generate new individuals, especially if clones are prohibited in the population. Two designs are clones of each other if all of the genetic information contained in the two chromosomes is duplicated exactly. The algorithm used in this thesis does not permit clones. Clones add no new information to the Pareto frontier so, in a multi-attribute decision problem, it is beneficial to prohibit clones. If clones are allowed, then the members of the population may have a tendency to gather around a few designs near the Pareto frontier and limit the number of other designs found on the frontier.

3.4.4 Subsequent Generations

After the first generation, new designs (offspring) are created by mating designs that possess dominant objective attributes. The offspring replace designs that possess dominated objective attributes (lethals). There are several possible methods to select parents and lethals, but only the tournament method is used and discussed. [3]

3.4.4.1 Selection

The tournament method randomly selects a fraction of the population to compete in a tournament. Each contestant in the tournament is compared against all other contestants to determine how many contestants dominate it.

If only one contestant is non-dominated, then it is declared the winner of the tournament and goes on to become a parent. If more than one contestant is non-dominated then the contestant with the lowest niche count is declared the winner. A niche count is a count of the number of other contestants that are "close" to an individual in objective attribute space. "Close" is a relative term that must be determined experimentally. Small populations require larger niche sizes so that the designs will more evenly spread over the Pareto frontier. Large populations can have smaller niche sizes and still maintain an adequate spread over the Pareto frontier. If more than one non-dominated contestant is tied for the lowest niche count, then the winner is chosen randomly from the non-dominated, low niche count contestants. [3]

The loser of the tournament, which is removed from the population, is the contestant that is dominated by the most contestants. If there is more than one most dominated contestant, then the one with the highest niche count is the loser. If there is

still a tie, then the loser is selected randomly from among the most dominated, highest niche count contestants. [3]

Two tournaments are held to select 2 parents and 2 lethals. After the second tournament, the parents are compared and the lethals are compared to ensure that the selections are not duplicates. If the same parent or lethal is selected, then the tournament process is repeated until unique parents and lethals are found. [3]

Tournament size is variable in the genetic algorithm. A large tournament size favors those members of the population that have good objective attributes in the current generation. In early generations, however, there is a fairly high probability that the best performers will not be the best performers in the later generations. To maintain genetic diversity, it is desirable to maintain some characteristics from weaker members, especially in early generations. At one extreme, if tournament size is set to the entire population, then only the over-all non-dominated individuals of the population will go on to reproduce, and it is possible that some valuable genetic information may be lost. At the other extreme, if only 2 members of the population are selected as contestants, then there is very little exploitation, and the search becomes nearly random.

3.4.4.2 Crossover

The parents selected from the tournament are mated using crossover to create 2 offspring. Each of the parents' chromosomes is cut at the same location. The location of the cut is randomly chosen. The portion of the chromosome to the right of the cut is swapped between the two parents to obtain two new offspring.

For example:

0101 | 00000 ⟹ 0101 | 11111

1010 | 11111 ⟹ 1010 | 00000

3.4.4.3 Mutation

After crossover, the chromosome of each offspring is randomly mutated. Each element of the offspring gene (each "1" or "0") has a probability of mutating (i.e. changing to "0" or "1"). The probability of each element mutating is the mutation rate. A high mutation rate has the effect of introducing more genetic information into the algorithm. If the mutation rate is 50%, the search is completely random. A very low mutation rate favors the genetic material that is currently in the population. In general, evolutionary algorithms perform best when the mutation rate is large for early generations and small for the final generations. This allows enough genetic information to be introduced early to maximize exploration, while still focusing the search to the best performers on the final generations to maximize exploitation.

3.4.4.4 Population

The offspring from the mating process are converted to base-10 design parameters and then evaluated for feasibility, performance, effectiveness and cost. The data associated with each of the offspring replace the data associated with each of the lethals in the population. Penalties are applied to objective attributes for infeasible designs. For early generations, no penalty is applied, but for late generations, the penalties are large to ensure that infeasible designs are seen as dominated. After each generation, the MOEs and cost are updated to reflect the appropriate penalty for the next generation. Applying a variable penalty maximizes exploration initially while maximizing exploitation at the end of the search.

3.4.4.5 Non-Dominated Designs

After each new design has been inserted into the population array, it is compared to all previously found non-dominated designs. If the design is infeasible, it is never saved as a non-dominated design. If a design is non-dominated, it is saved in the non-dominated array. A check is then performed to determine if the newly found non-dominated design dominates any of the designs already in the non-dominated array. If any designs are now dominated, they are removed. A final check is made to determine if the new design has the same MOEs and cost as a design that has already been found to be non-dominated. If such a design is found, the design parameters are checked to determine if the design is a clone or a new design. If it is a clone, it is rejected; if it is a unique design, it is saved.

3.5 Presentation to the Decision-Maker

The decision-maker is presented with a plot that represents the Pareto frontier. If two MOEs and cost are used as the objective attributes, then the horizontal and vertical axis each represent one of the MOEs. The Pareto frontier is plotted for each cost of interest. Each curve represents a different cost.

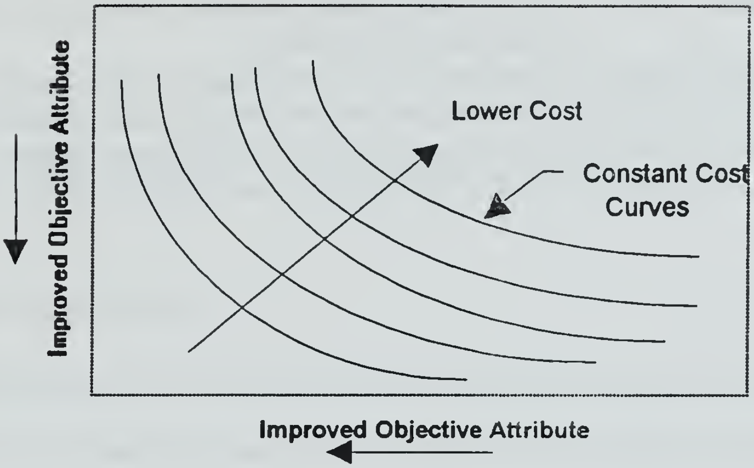

Figure 3-4 Pareto Frontier with 3 Objective Attributes

The decision-maker can then make a final decision on which design or designs should be carried forward for further development. If Cost as an Independent Variable (CAIV) is being used by the decision-maker, then focus can be narrowed to the curve representing the program budget and the best tradeoff of the 2 MOEs can be made. Often the decision-maker will focus in on the "knee in the curve". A "knee in the curve" represents a location on the Pareto frontier where the slope of the curve transitions from very steep to very shallow. The steep and shallow portions of the curve indicate regions where a large gain can be made in one MOE for a small sacrifice of the other MOE (or conversely, a large sacrifice must be made in the other MOE for small gains in one MOE). At the "knee", the trade from one MOE to gain in another MOE is nearly equal.

If the project budget has not been set, then analysis of the proper cost must also be made. At locations where the curves are very close together, very little gain is made for additional expenditure. At locations where the curves are separated by a large distance, small additional expenditures generate large gains in effectiveness.

No matter which design is finally chosen, however, this type of analysis provides a set of designs that are not dominated by any other designs. The decision-maker is given the opportunity to choose from among a group of non-dominated designs.

4
Detailed Process

This chapter provides the detailed process proposed for LSV II multi-attribute decision analysis. It is an application of the method proposed in Chapter 3.

4.1 Design Parameters

Design parameters are the vehicle's physical characteristics that are varied in an attempt to maximize the effectiveness of LSV II. Only the most important design parameters are varied to demonstrate the proposed decision method. The goal is to choose parameters that have the greatest impact on the effectiveness and cost of the vehicle. For the purposes of this study, parameters are also chosen to ensure information is available to analyze the effects of varying the parameters.

Design Parameters
Maximum Hull Diameter (D)
Length to Diameter Ratio (L/D)
Shape Factor Forward (N_f)
Shape Factor Aft (N_a)
Battery Type
Battery Size
Hull Coating Thickness
Sonar Type

Maximum hull diameter is varied between 8 and 15 feet. The lower limit is chosen to ensure that the electric propulsion motor chosen for the vehicle fits in the hull. The upper limit is an estimate of the maximum feasible diameter due to limits on handling equipment.

Length to diameter ratio is varied between 6 and 13. The lower limit is chosen because drag is near a minimum near this ratio. The upper limit is chosen because

current submarine design practice limits L/D to approximately 13 due to high values of drag above this value. [16]

Shape factors forward and aft are allowed to vary between 1.75 and 4.00. These factors define the shape of the hull. Small shape factors yield fine hulls, while large shape factors yield full hulls. The range chosen represents the bounds of current submarine design. [16] The equations for diameter as a function of shape factor and longitudinal location are found in the geometry section of this chapter (Section 4.4.1).

Battery type is chosen to be one of four specific types proposed by GNB Technologies.[17] Details of each battery type are discussed in the subsections on weight (Section 4.4.2) and battery energy consumption (Section 4.5.3).

Battery Type	Battery Life	Performance	Acquisition Cost	Risk
3 year Lead Acid	3 year	Low	Low	Low
1 year Lead Acid	1 year	Medium	Low	Medium
Bi-Polar Lead Acid	3 year	Medium	Medium	Medium
Nickel-Zinc	3 year	High	High	High

Table 4-1 Battery Characteristics

Battery power for each battery type is varied as a design parameter from 3000 to 6500 kWe (kilowatt electric) at the five-minute rating. The range was chosen to be representative of the range of designs currently under consideration.

Hull coating thickness is varied from 0 to 3.5 inches. Hull coating reduces radiated noise from the LSV II and reduces the expected uncertainty band in sonar performance. Because hull coating compresses with increased depth, the trim tank must be sized to compensate. The maximum thickness was chosen as representative of the range of coatings currently under consideration.

Sonar type is allowed to be either the baseline sonar currently installed at the Acoustic Research Detachment (ARD) Facility or a proposed sonar upgrade. The proposed upgrade requires an initial monetary investment, but reduces the expected uncertainty band in sonar performance. [18]

4.2 Binary Representation

Each potential LSV II variant is represented by a chromosome composed of 8 genes that represent the design parameters. The genes and chromosomes are sized for the initial model as indicated in the Table 4-2. Because large gaps in the values of the design parameters cause large gaps in the effectiveness plot, the gene sizes are increased in subsequent iterations to further refine the non-dominated frontier.

	Gene Size	Number of Parameter Values
Hull Diameter (D)	3	8
Length to Diameter Ratio (L/D)	3	8
Shape Factor Forward (N_f)	3	8
Shape Factor Aft (Na)	3	8
Battery Type	2	4
Battery Size	4	16
Hull Coating Thickness	3	8
Lake Sonar Type	1	2
Total Chromosome Size	22	4,194,304

Table 4-2 Chromosome and Gene Sizes for Initial Model

The subroutine "Decode" converts the binary string into the base-10 value of each design parameter.

4.3 Random Selection of First Generation

The first generation of LSV II designs is created by random selection. Each element of the binary chromosome string is randomly assigned a "0" or "1". After each

member of the first generation is created, it is decoded into base 10 and then evaluated for feasibility, performance, effectiveness and cost.

4.4 Balance and Feasibility of Design

The subroutine "Balance" determines the geometry, weight and feasibility of the design based on the design parameter chromosome.

4.4.1 Hull Geometry

The volume, longitudinal center of buoyancy and wetted surface area of the hull are calculated as functions of D, L/D, N_a and N_f using numerical integration. The hull is assumed to be a body of rotation with three separate sections: forward body, parallel mid-body and aft body. [16,19]

Forward Body: $L_{fwd} = 2.4 * D$

$$D_{fwd} = D\left[1-\left(\frac{x_{fwd}}{L_{fwd}}\right)^{N_f}\right]^{\frac{1}{N_f}}$$

Mid Body: $L_{mid} = (L/D - 6) * D$

$D_{mid} = D$

Aft Body: $L_{aft} = 3.6 * D$

$$D_{aft} = D\left[1-\left(\frac{x_{aft}}{L_{aft}}\right)^{N_a}\right]$$

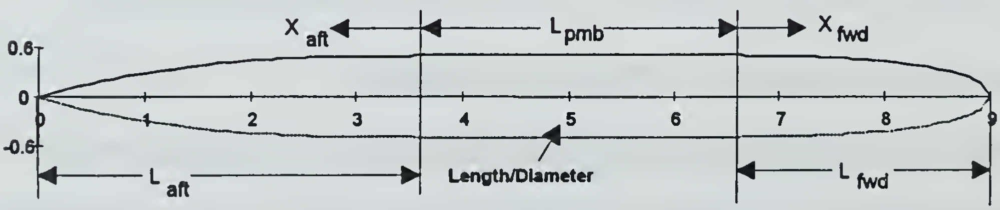

Figure 4-1 Hull Geometry

After the basic hull geometry is calculated, the volume of the hull coating is calculated by multiplying the wetted surface area by the coating thickness. The submerged volume of the hull coating is assumed to be 60% of the surfaced volume to account for compression. [4] The wetted surface area of the hull with coating is also calculated at this point for use in resistance calculations.

The volume of the trim tank is then sized to compensate for coating compression and an additional 10% margin. The length of the trim tank is calculated assuming that the tank is in the parallel mid body and uses 90% of the total hull volume in this section.

The length of the forward and aft main ballast tanks (MBT) are calculated using numeric integration assuming that total reserve buoyancy is 10% (6% forward and 4% aft). An additional 1% is added to each tank to account for equipment in each MBT.

The final aspect of geometry is the geo-similitude of the vehicle. The geo-similitude check determines if the vehicle has the same shape as either SSN-21 (USS Seawolf) or NSSN (New Attack Submarine). Being geometrically similar to a previously built submarine, or one to be built in the near future, adds value to the hydrodynamic measure of effectiveness. The subroutine "Calc_HAMOE" determines the geo-similitude by comparing length to diameter ratio (L/D) and shape factors forward and aft (N_f and N_a). If all 3 of these parameters are within 10% of these parameters for the full-scale vehicle, then the LSV is credited with geo-similitude. Otherwise, it is assigned a value of no geo-similitude. Hull characteristics for NSSN and SSN-21 are presented in Table 4-3. [20]

	NSSN	SSN-21
L/D	11	8
N_f	2.5	2.75
N_a	2.75	3.00

Table 4-3 Hull Characteristics for NSSN and SSN-21

4.4.2 Weights and Internal Arrangements

The weights of the LSV II are calculated by using ratios to known and proposed designs. Design LSV A1, the Newport News baseline design of a New Attack Submarine geo-similitude, is the reference for most of the weight ratios. Longitudinal center of gravity (LCG) and vertical center of gravity (VCG) are calculated by estimating the equipment location within the hull (Figure 4-2). [4]

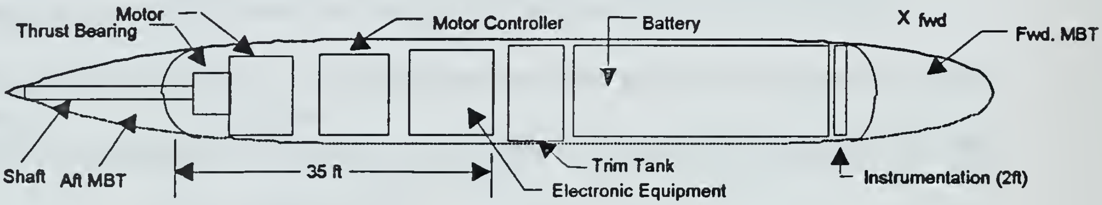

Figure 4-2 Internal Arrangements Drawing

Weight Group 1 (Structure) is calculated by assuming that structural weight is proportional to wetted surface area. Since each LSV design has the same operating depth, structural weight is primarily a function of the surface area, assuming hull thickness and frames will be sized approximately the same. The ratio of weight group 1 to wetted surface area for design A1 is assumed to be constant. LCG and VCG are in the same relative location as A1.

Weight Group 2 (Propulsion), with the exception of the propulsor, is assumed to be the same as A1 since all designs have the same propulsion motor and controller. The weight of the propulsor is calculated separately and is assumed to be included in the margin of the vehicle. All propulsion equipment is assumed to be identical to A1, including propulsion motor, motor controller, thrust bearing and shafting.

Weight Group 3 (Electric Plant) is separated into 3 sub-groups: battery, cable and other. Battery weight is calculated from a weight specific power provided by GNB Technologies [17]. Battery LCG is placed at the center of the battery with the forward end of the battery placed 2 feet aft of the forward MBT. Battery length is calculated from volume specific power assuming the battery is in parallel mid-body and that 20% of the space is used for battery volume with 65% for structure and 15% for cooling.

Battery Type	Weight Spec Power (kWe at 5 min/Lton)	Volume Spec Power (kWe at 5 min/ft^3)
3 year Lead Acid	45.2	4.87
1 year Lead Acid	62.2	5.70
Bi-Polar Lead Acid	107	5.00
Nickel-Zinc	182	13.8

Table 4-4 Battery Specific Powers

Cable weight is calculated by multiplying cable length for each design by the cable linear density from design A1. Cable linear density is cable weight for A1 divided by cable length for A1. The cable is assumed to extend from the battery center to the motor controller. The other electric plant weight is assumed to be the same as for A1. All VCGs for weight group 3 have the same relative location as A1.

Weight Group 4 (Command and Control) is assumed to be the same as A1 with an LCG 26 feet forward of the aft MBT and a VCG in the center of the vehicle.

Weight Group 5 (Auxiliaries) includes cooling and other. Cooling weight is assumed to be proportional to battery power. Design A1 is used to obtain the cooling weight to battery power ratio. The LCG for cooling is assumed to be 26 feet forward of the aft MBT, with the VCG in the center of the vehicle. All other items in Group 5 are assumed to scale to the length of the vehicle. The LCG for Weight Group 5 is assumed to be 26 feet forward of the aft MBT, with the VCG in the center of the vehicle.

Weight Group 6 (Outfit and Furnishings) is broken into hull coating and other. Hull coating weight is calculated by assuming the uncompressed coating has a specific volume of 60 cubic feet per long ton. All other Group 6 items are assumed to scale by length with the same weight to length ratio as in design A1. The LCG and VCG for each sub-group are assumed to be in the same relative location as A1.

Weight Group 7 (Instrumentation) is assumed to scale to length with the same weight to length ratio as A1, assuming that the longer vehicle requires more sensors and cables. LCG and VCG are assumed to be in the same relative location as A1.

4.4.3 Feasibility

Once the geometry and weights have been determined, the feasibility is checked to ensure that all components fit within the length of the hull and that the vehicle displaces at least as much as it weighs. The margin is then calculated.

The total length of all components is calculated by summing all variable and fixed components in the stack length. The lengths of the forward and aft MBT, battery and trim tank are calculated in the geometry subroutine. The fixed components are

propulsion motor and shafting (13 feet), propulsion motor controller (12 feet) and electronic cabinets (12 feet) for a total of 37 feet.

The weight of the vehicle without stability lead is compared to 90% of submerged displacement to ensure the vehicle can be made neutrally buoyant with the MBTs filled. The margin of the vehicle is then calculated by determining the heaviest weight that can be placed at the stern of the vehicle (i.e. the propulsor) with compensating trim lead placed in the forward MBT 5 feet aft of the forward perpendicular, while maintaining the ship neutrally buoyant and stable.

4.5 Measures of Performance

The next step of the process is to calculate the Measures of Performance (MOPs) for the vehicle. MOPs are those observable characteristics that are outputs of the design process and affect the overall effectiveness of the vehicle. The subroutine "Calc_MOPS" determines maximum vehicle speed, number of trials possible at Froude scale maximum speed, number of acoustic trials possible and the maximum speed obtained during acoustic trials.

4.5.1 Vehicle Resistance

All of the MOPs require knowledge of the vehicle resistance at various speeds. "Froude's hypothesis is assumed and the frictional and residual resistances are calculated separately." [19] Total resistance is calculated by determining the coefficients for frictional, residual, correlation and appendage resistance. [16]

Frictional resistance coefficient is calculated from the ITTC formula [19]:

$$C_f = \frac{0.075}{[\log_{10}(Rn)-2]^2}$$

Rn = Reynold's Number
= $V_k(1.6886)L/u$
L = vehicle length (feet)
V_k = vehicle speed (knots)
u = Kinematic viscosity (ft^2/sec)

Residual resistance coefficient is calculated from the following equation derived from parametric studies [19]:

$$\frac{C_f + C_r}{C_f} = 1 + 1.5\left(\frac{D}{L}\right)^{3/2} + 7\left(\frac{D}{L}\right)^3 + .002\left(C_p - .6\right)$$

Correlation allowance (CA) is assumed to be 0.0004 for all vehicles.

Appendage resistance includes resistance from the sail and from other appendages. Sail drag coefficient is assumed to be 0.009. A typical sail on a full size submarine is approximately 1,000 square feet. Assuming a typical full scale submarine has a diameter (D) of 30 feet and a length (L) of 300 feet, the ratio of sail area to LD is 1/9. [19] Therefore,

$$\begin{aligned}(\text{sail area})(C_d\ \text{sail}) &= (1/9)(LD)(0.009)\\ &= LD/1000\end{aligned}$$

Likewise, typical appendages (rudder, planes, etc.) are such that:

$$(\text{Other appendage area})(C_d\ \text{other appendages}) = LD/1000$$

The total appendage area multiplied by drag coefficients is the sum of the above two results:

$$C_{app} = LD/500.$$

Using all of the above coefficients and converting to horsepower, the resulting powering equation is [19]:

$$EHP_{total} = (0.00872)V_k^3[WS_{cot}(C_f + CA + C_r) + LD/500]$$

4.5.2 Maximum Speed

Maximum speed is limited by either the installed propulsion motor or the battery. The motor for all variants is identical and is rated at 6000 hp. The battery power rating is a design parameter input variable. The maximum speed is evaluated at the 5-minute battery power rating. It is assumed that 89% of the rated battery power is available to the motor. The lower of the value of battery power available and motor horsepower is used as maximum shaft horsepower (SHP) to calculate maximum speed. A propulsive coefficient of 0.8 is applied to the SHP of all variants to obtain effective horsepower (EHP). An initial guess of 30 knots is made for the maximum speed to obtain an initial guess for Reynolds number. A new estimate for maximum speed is then obtained from the powering equation. A new Reynold's number is calculated, and this process is repeated until the speed estimate and the speed from the powering equation converge to within 0.01 knots.

4.5.3 Battery Energy Consumption

To calculate endurance runs at either high speeds or endurance speed, the amount of energy available in the battery must be determined. When the amount of energy in the battery approaches zero, then the data gathering trial must end. Each battery type has a

characteristic curve of rated time as a function of power level. At low power levels, the battery can provide power significantly longer that it can at high power levels. When this rating on a log scale curve is plotted over the range of interest, the result is nearly linear, with each type of battery having a different slope. The slope for the same type of battery over different power ratings is assumed constant.

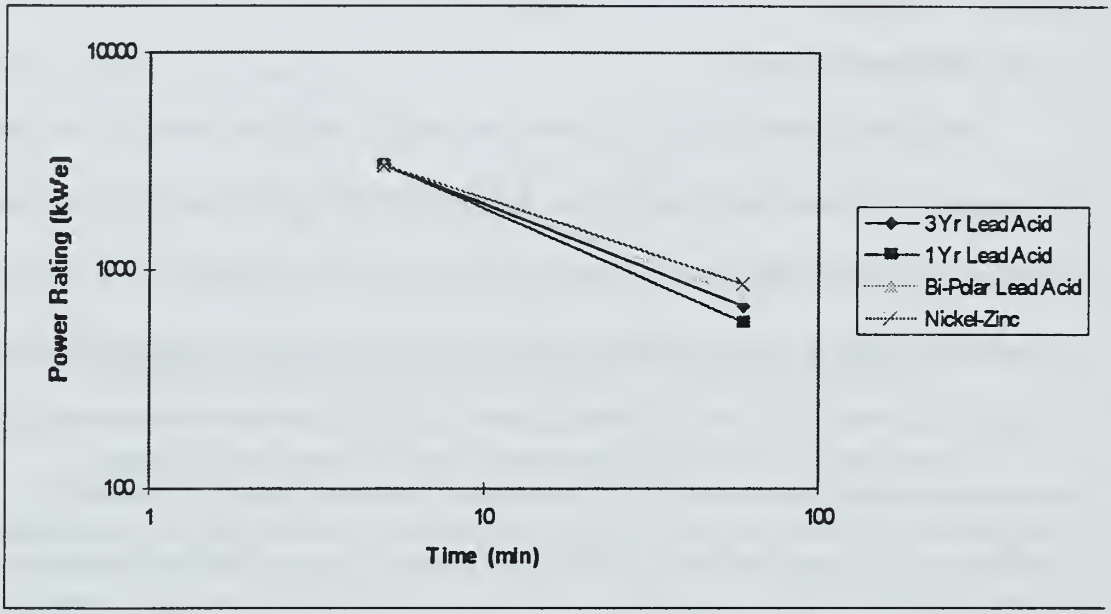

Figure 4-3Battery Power Ratings as a Function of Time at Power

The fraction of total battery energy used at a particular power is equal to the time spent at that power level divided by the battery rated time at that power level. For example, if a vehicle spends 2 minutes using 3000 kWe and the rated time for 3000 kWe is 5 minutes, then the vehicle has used 40% of its available energy.

4.5.4 Hydroacoustic Runs

The measure of hydroacoustic effectiveness requires determination of the number of runs that can be performed starting at 18.5 knots and increasing speed in subsequent

runs in increments in 5 knots. The final run may be performed at an increment of less than 5 knots. Each attempt to obtain hydroacoustic data starts with submerging, pumping out 90% of the trim tank water, and proceeding to the desired depth for the test. The vehicle must remain at 8 knots until half of the trim tank has been pumped, after which time speed is reduced to 4 knots. If the time submerged is less than 30 minutes, then the vehicle must loiter at 4 knots to complete the instrumentation start-up procedure. [4,21]

The trim system pump for the LSV has a rated capacity of 30 gal/min. Assuming the water is pumped out at a depth of 200 feet and the efficiency from the battery to water pumped overboard is 70%, then 100 kW is required for the time that the pump is running. The time the pump must run is 90% of the volume of the trim tank divided by the pump capacity.

The power required to loiter at 4 and 8 knots is calculated from the powering equation. The power used at the beginning of the run is the sum of the pump power and propulsion power at 8 knots. The fraction of battery energy used is then calculated for the time to pump half of the trim tank. The next step is to reduce speed to 4 knots and pump the remainder of the trim tank. Again battery energy is calculated. The vehicle then secures the pump and continues to loiter at 4 knots until the time submerged is greater than 30 minutes. Battery energy is again calculated.

The vehicle is then ready to start its first run at 18.5 knots and travel through the acoustic range. The time required to complete this evolution is approximately 3000 yards divided by the vehicle speed. The actual distance on the range is somewhat less than 3000 yards, but the additional distance allows for acceleration. The power used by the vehicle is calculated from the powering equation, taking into account PC and electrical to

mechanical efficiency. Using this power over the time to complete the run, the fraction of battery energy used is calculated. If the total battery energy remains positive, then the vehicle has successfully completed one run. If the calculated total battery energy remaining is less than zero, then the vehicle does not have enough battery energy to complete the run.

Before a second run can be started, the vehicle must loiter for 30 minutes at 4 knots to reposition for the next run and reset the instrumentation. The second run is attempted at 23.5 knots (5 knots faster than the first run). Again the power and time required for this run are calculated along with the fraction of battery energy used. If the total battery energy remaining is positive, then another successful run is completed. If not, the total battery energy is returned to energy available after the last loiter between runs, and the speed is reduced from the previous unsuccessful run in 0.25 knot increments until the maximum speed for hydroacoustic data collection is found. If the attempt at the five-knot increase is successful, then the speed is again increased 5 knots (28.5 knots for run 3) and the process is repeated until the maximum speed for hydroacoustic data collection is found. A final check is made to ensure the maximum speed calculated for hydroacoustic data collection does not exceed the vehicle maximum speed. If it does, the maximum hydroacoustic speed is set to maximum vehicle speed.

4.5.5 Hydrodynamic Runs

The final MOP calculated is the number of data collection runs that can be performed at Froude scale maximum speed. Assuming LSV is scaled to a submarine with a 10,000 Lton submerged displacement, the scaling factor and Froude scale maximum speed are:

$$Scale = \left(\frac{Displacement_{sub}}{10{,}000 lton} \right)^{1/3}$$

$$V_{Fr} = V_{\max} (Scale)^{1/2}$$

The battery power required to propel the vehicle at this speed and the battery energy for the time required to cover the 3000 yard course are then calculated. The total number of Froude runs possible is the truncated result of battery energy available divided by the energy required for each run.

4.6 Cost

The subroutine "Cost" calculates acquisition cost and discounted total ownership cost for each LSV II option that is evaluated. All cost estimates are based on the LSV II A1 Total Ownership Cost Estimate [22] and are referenced to constant FY 98 dollars. Dollars spent in future years are discounted at 6% per year.

4.6.1 Acquisition Cost

Acquisition cost is estimated by multiplying each weight group calculated by the weight subroutine by a cost estimating relationship (CER) extracted from the cost estimate for A1. The CERs are obtained by dividing the cost for each weight group by the weight of that group in the estimate for A1. The weight groups that do not vary between the variants are assigned a constant cost. Instrumentation is also assigned a constant cost. Group 0, 8, and 9 are assigned a constant cost for design engineering, ship support services, computer costs and travel.

Weight Group	CER ($K/Lton)	Constant Cost ($K)
1 - Structures	76.0	
2 - Propulsion		$1,977
3 - Other than Battery	171	
4 - Command and Control		$6,740
5 - Cooling	763	
5 - Other Auxiliaries	763	
6 - Outfitting (Excluding Coating)	683	
7 - Instrumentation		$261
0,8,9 - Support/Engineering		$19,252
Total constant cost		$28,230

Table 4-5 Cost Estimating Relationships (CERs)

Battery cost is estimated by using a CER for battery power at the 5-minute rating. The basic battery CER is calculated from the A1 cost estimate and the A1 battery power with a 3-year lead acid battery. The remaining batteries are all priced relative to the baseline battery.

Battery Type	Relative Cost
3-year Lead Acid	1
1-year Lead Acid	1
Bi-Polar Lead Acid	1.5
Nickel-Zinc	2

Table 4-6 Relative Battery Cost

Hull coating cost is calculated by determining one CER for coating volume and another CER for coating surface area. The volume CER is 0.897 $\$K/ft^3$ and the surface area CER is 0.234 $\$K/ft^2$. The volume CER accounts for material cost and the surface area CER accounts for installation cost. [23]

The final acquisition cost is the sum of all the above costs with an additional 10% contractor fee added as profit.

4.6.2 Discounted Total Ownership Cost

The Discounted Total Ownership Cost (DTOC) includes acquisition cost, sonar upgrade cost, yearly operational cost, upgrade cost and disposal cost. If the improved

sonar system is installed at Lake Pend Oreille, the upgrade cost of $3.0 million charged in the first year of operation. Yearly operational cost is estimated to be $7.17 million for each of the 20 years of expected operation. The upgrade cost is estimated to be $1.1 million every 5 years with full battery replacement every 3 years. The 1-year lead acid battery must have a full battery change every year. Disposal cost is estimated to be $1 million and occurs in year 20 at the end of life.

	Cost ($K)	Frequency
Acquisition Cost	Calculated	Beginning of Program
Sonar Cost	$3,000	Beginning of Program
Yearly Cost	$7,170	Yearly
Upgrade Cost	$1,100	Every 5 years
Battery Upgrade	Battery cost	Every 3 years or yearly
Disposal Cost	$1,000	20 years

Table 4-7 Life Cycle Cost Summary

The discount rate for all calculations is assumed to be 6.0%. This is a number close to the average of the government discount rates over the last 20 years. [10] Selection of discount rate is a complicated issue and an entire thesis could be devoted to this topic. The current government discount rate is probably too low and the discount rate used in the 1980s is probably too high. The value selected is an adequate compromise.

4.7 Hydroacoustic Measure of Effectiveness

One of the primary purposes of the LSV II is to measure the acoustic signature of the propulsor. The important information to be gained from the hydroacoustic experiments is the acoustic signature of the propulsor at low speeds (assumed to be 15 knots for this thesis). Because of competing noise sources from the vehicle, however, the propulsor acoustic signature cannot be directly measured at 15 knots. Acoustic

measurements must be made at several higher speeds and the data extrapolated down to 15 knots. The hydroacoustic measure of effectiveness (HAMOE) for LSV II is the expected acoustic uncertainty band at 15 knots.

From previous analysis and experience with LSV I, it is expected that radiated noise from the LSV propulsor is measurable above 18 knots. Below this value competing noise sources make propulsor acoustic measurement difficult. To predict the propulsor acoustic signature below this speed, two or more measurements must be made at different higher speeds and the data extrapolated down to the desired speed of 15 knots. The two major factors that affect the size of the uncertainty band at 15 knots are the uncertainty of the measurement at high speed and the speeds at which the measurements are performed. [24]

The expected acoustic error band at 15 knots can be represented graphically by plotting acoustic signature (dB) vs. speed. (See Figure 4-4 and 4-5)

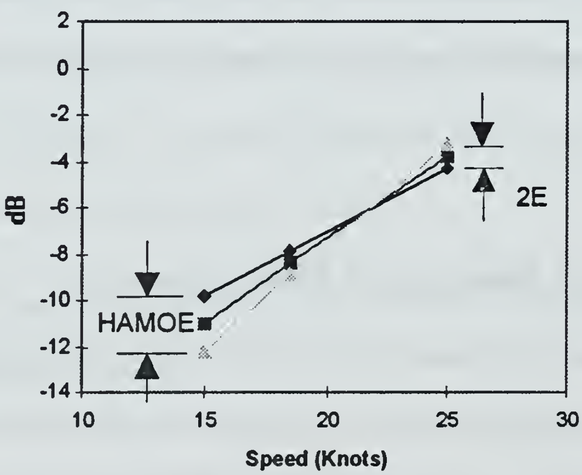

Figure 4-4 Expected dB Uncertainty with Max Hydroacoustic Speed 25 knots

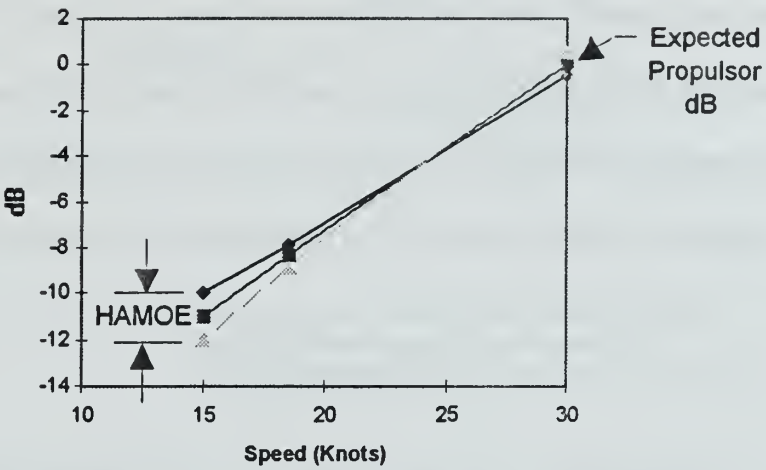

Figure 4-5 Expected dB Uncertainty with Max Hydroacoustic Speed 30 knots

The center line of each plot represents the expected acoustic signature to be measured by the sonar system. The top and bottom lines on the figure represent the error band (±E at the speed of measurement). Extrapolating data from the high speed, high dB point through the low speed, low dB point down to 15 knots gives one side of the uncertainty band. Likewise, extrapolating from the high speed, low dB point through the low speed, high dB point down to 15 knots provides the other side of the total uncertainty band. The distance between the upper and lower point at 15 knots represents the uncertainty band, or HAMOE. The uncertainty band is reduced (HAMOE improved) if the uncertainty at measurement speed is reduced or if the highest speed measured is increased. Comparison of the two graphs shows the improvement in HAMOE for increased maximum speed.

The expected uncertainty band is assumed to be constant for a particular design at any speed greater than 18.0 knots. The two factors that affect the size of these uncertainty bands are sonar type and hull coating thickness. A nominal uncertainty is

expected to be approximately $\pm$ ½ dB. For this thesis it is assumed that a design with the baseline sonar and no hull coating has an uncertainty band of $\pm$ 1 dB. It is also assumed that the improved sonar halves the expected uncertainty band. Hull coating is assumed to reduce the uncertainty band with an inverse relationship with its thickness. The equation used in the program to determine one-half of the expected uncertainty band is [24]:

$$E = \frac{1}{(Sonar)(1 + T_{cot})}$$

E = Expected Uncertainty Band (dB)
Sonar =1 if Baseline
=2 if Upgrade
T_{cot} = Hull coating thickness (inches)

This equation is only a rough estimate of the expected uncertainty band, but should provide and demonstrate the basic trends associated with sonar and coating performance. Before a decision can be made using this method, this uncertainty band must be refined to reflect the true characteristics of the hull coating performance and sonar capabilities. The numbers used in this thesis are expected to be of the correct order of magnitude and correct in trend. Further refinements were not attempted to avoid classification issues with the sensitive nature of acoustic data in the United States Navy submarine program.

The HAMOE (i.e. the uncertainty band at the speed of interest) is calculated using the following equation developed by Blake [24]:

$$HAMOE = 2 * E * \frac{LOG_{10}\left(\frac{\sqrt{V_{MAX} V_{MIN}}}{V}\right)}{LOG_{10}\left(\frac{V_{MAX}}{\sqrt{V_{MAX} V}}\right)}$$

E = Expected uncertainty band at measured speed
V_{MAX} = Maximum speed of hydroacoustic run
V_{MIN} = Minimum speed of hydroacoustic run (18.5 kts)
V = Speed of interest (15 kts)

This equation calculates the HAMOE labeled in Figures 4-4 and 4-5.

The low hydroacoustic speed for all LSV variants is taken to be 18.5 knots. From experience with LSV I, it is desirable to have a separation of approximately 5 dB between data points. The expected relationship between speed and acoustic signature is between $40\log_{10}$(Speed) and $60\log_{10}$(Speed), or approximately $50\log_{10}$(Speed) [24]. This is represented by the center lines on Figures 4-4 and 4-5. Near the speeds of interest, this implies that each successive run should be separated by no more than 5 knots to ensure the 5-dB separation as shown by the following equation:

$$50 \log_{10} (23.5 \text{ knots}) - 50 \log_{10} (18.5\text{knots}) = 5\text{dB}$$

This is the reason that the measure of performance subroutine calculates the number of high-speed runs starting at 18.5 knots and increasing subsequent runs in 5 knot increments. The assumption is made that all runs must be done on the same battery charge to ensure the same acoustic conditions for all runs.

4.8 Hydrodynamic and Flexibility Combined Measure of Effectiveness

The hydroacoustic and flexibility attribute involves more than one performance metric. Expert opinion is used to establish and synthesize the relative value of 3 measures of performance into a CMOE: Number of Runs at Froude Scale Maximum Speed, Margin and Geo-similitude. Two methods of collecting this expert opinion are investigated: Multi-Attribute Iso-effectiveness (MAIE) and Analytical Hierarchy Process (AHP). MAIE is used in the computer model to synthesize the CMOE and AHP is used for comparison purposes. Appendix A contains the survey results from the two methods.

Both methods require the determination of goals and thresholds for each variable. The following goals and thresholds are used:

Number of Runs at Froude Scale Speed that can be performed on one battery charge.
Goal = 10, Threshold = 7

Amount of margin that is available for future growth, including propulsor installation.
Goal = 12%, Threshold = 3% (Variant A1 currently has a value of 6.3%)

The type of geo-similitude that is chosen.
Options: NSSN, SSN-21, None (i.e. has "submarine-like shape")

Goals represent the best value the decision maker believes to be obtainable with the technology available in the time frame of the project, or the value at which further improvement no longer adds significant improvement to the project. Thresholds represent the value of worst acceptable performance. Below this value, it is considered not worth continuing with the project.

If a variant achieves values above the goal, no additional credit is given. It is treated the same as if it had only achieved the goal. If any value is below the threshold,

the LSV is assumed to be not feasible. Selection of appropriate variables and goals and thresholds is extremely important, because if this first step of the process is flawed, the remainder of the process does not give meaningful results.

The AHP method requires the expert to make a set of pair-wise comparisons using a questionnaire. First the relative importance of each of the variables is compared. Specifically, the expert must compare Geo-similitude to Margin, Geo-similitude to Number of Froude Scale Runs (FSRs), and Margin to Number of Froude Scale Runs. Each of the specific values under each category is then compared to each other specific value within its category. All comparisons are on a scale from 1 to 9, with 1 indicating the choices are equal and 9 indicating that one option is extremely more important than the other. The data is then analyzed using "Expert Choice" software in the distributive mode. Appendix A contains the AHP survey and results. [15]

The input required for the Multi-Attribute Iso-effectiveness is obtained by having the expert answer a set of questions to generate a set of iso-effectiveness curves. An iso-effectiveness curve represents the combination of characteristics with which the decision-maker is equally satisfied. For example, if one of the variables is held constant, how much change is required in each of the two remaining variables to give equal effectiveness? Specifically, if geo-similitude is held constant, what value of margin combined with 9 Froude Scale Runs gives equal effectiveness to 10 Froude Scale Runs and 3% margin? This question is occasionally difficult for experts to answer initially, so the expert is encouraged to bracket the answer until the equivalence point is reached. For example, 12% margin is probably preferred, but 3.5% is probably not. Appendix A gives the complete survey along with a plot of iso-effectiveness lines.

The information from the iso-effectiveness curves is entered into the subroutine "Calc HAMOE." The output of HAMOE is an "equivalent margin." If the geo-similitude is "none" and the Number of Froude Scale Runs is the threshold value (7), then the equivalent margin is the vehicle margin. If however, geo-similitude or FSRs is greater than the threshold, then the equivalent margin is increased to the point that the decision maker is equally satisfied with the variant's attributes and one with the equivalent margin, no geo-similitude and threshold FSRs.

To graphically see the process of equivalent margin, assume the LSV variant under consideration has an SSN-21 geo-similitude, 8% margin and is capable of 8 FSRs. Entering the Iso-Effectiveness with Froude Run Constant graph (Figure 4-6) at SSN-21, 8% yields a point between the top two iso-effectiveness lines. Interpolating between the two lines at the no geo-similitude location to the same linear proportion as at the SSN-21 geo-similitude yields an intermediate equivalent margin of 9%. If the FSRs were at the threshold value, this would be the final equivalent margin.

Since FSRs equals 8, the Iso-Effectiveness with Geo-similitude constant graph (Figure 4-7) must be entered at 8 FSRs and the intermediate equivalent margin of 9%, which yields a point between the top two iso-effectiveness lines on this graph. Interpolating between the two lines at the FSRs equal 7 location yields the final equivalent margin of 9.5%. This is the final value for the hydrodynamic and flexibility measure of effectiveness.

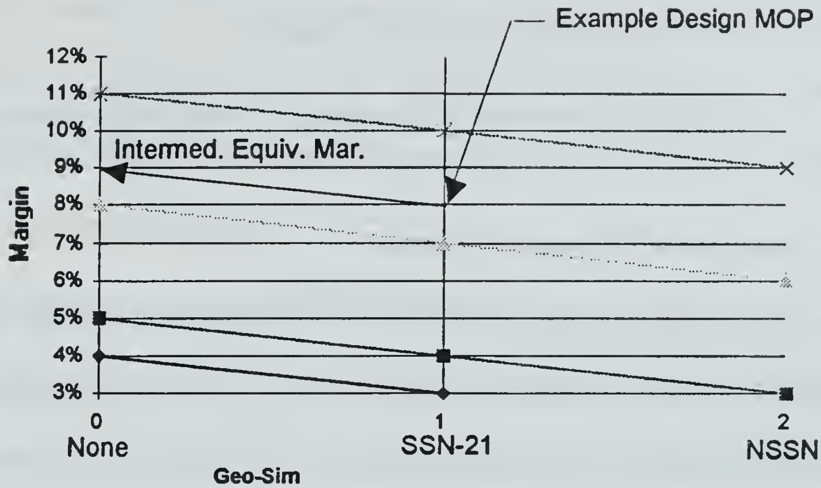

Figure 4-6 Iso-effectiveness with Froude Runs Constant

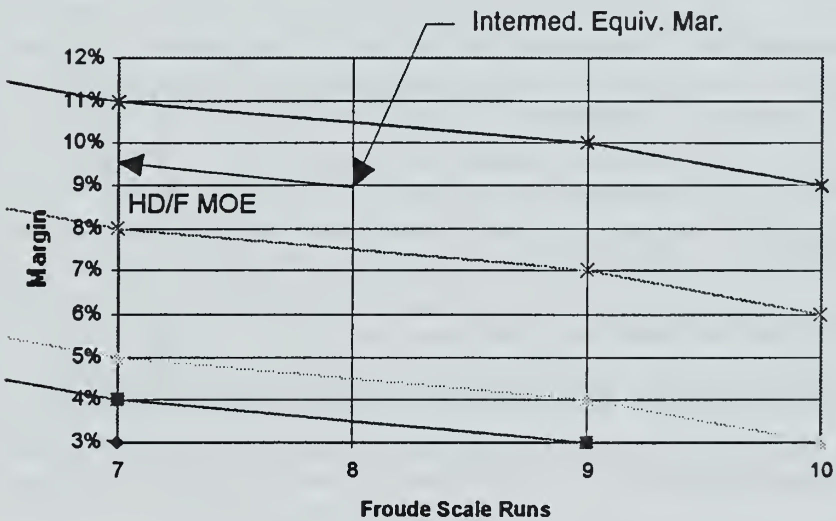

Figure 4-7 Iso-effectiveness with Geo-sim constant

4.9 Generation of New Designs

Once the initial population is generated randomly, new designs are created through the genetic algorithm:

1. Parents and lethals are selected based on dominance and niche count.

2. Children are created by crossover and mutation.

3. Children replace lethals in the population.

4. Children are compared with designs in non-dominated array.

4.9.1 Selection of Parents and Lethals

Parents and lethals are selected through a tournament process. A fraction of the population is randomly chosen to participate in a tournament. The initial tournament size is set to be equal to 10% of the population size. The member in the tournament with the best objective attributes is selected to be the parent, while the member with the worst objective attributes is selected to be the lethal. Each member in the tournament is compared to each other member in the tournament, and a count is maintained as to how many members in the tournament dominate each other member. The tournament winner is the one that is not dominated by any other member of the tournament. If more than one member in the tournament is non-dominated, then the member with the lowest niche count is chosen. A niche count is a count of the number of other members in the population that are "close" in objective attribute space. "Close" is very subjective and obtained experimentally. If more than one of the non-dominated tournament members tie for the lowest niche count, then the winner is chosen randomly from those non-dominated tournament participants with lowest niche count.

	Niche Tolerance
DTOC	$4M
HAMOE	0.3
HD/F CMOE	0.03

Table 4-8 Niche Tolerances for Cost and MOEs

The loser of the tournament is the one that is dominated by the most other members of the tournament. If more than one ties for most dominated, then the one with the highest niche count is chosen as the lethal. If there is still a tie after niche count comparison, the loser is randomly chosen from among the most dominated tournament participants with lowest niche count.

Once the first parent and lethal are chosen, the tournament process is repeated to select a second parent and lethal. A check is made to ensure that a duplicate parent or lethal is not selected. If a duplicate is selected, the tournament is repeated until non-duplicated parents and lethals are obtained.

4.9.2 Crossover and Mutation

The two parents are taken by the subroutine "Mate" in binary form and 2 children are returned. The binary strings representing each parent chromosome are randomly broken in the same location. The portion of the chromosome after the break is then swapped between the two parents to create two children by crossover. Each child is then modified through mutation. Each element of each gene (i.e. each 0 or 1) has a probability of mutating (i.e. changing to 1 or 0) equal to the mutation rate. The mutation rate changes from a high value at the beginning generations (10%) to a low value at the end generations (.1%). This allows more effective exploration at the beginning generations, while having better exploitation at the end. (See Figure 4-8)

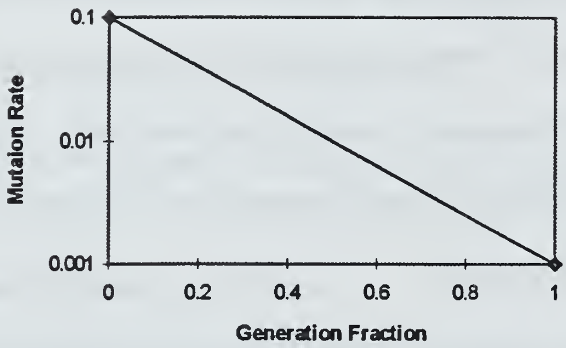

Figure 4-8 Mutation Rate as a Function of Generation

4.9.3 Population

After each member is evaluated, the LSV characteristics, MOPs, MOEs and cost are stored in the "Population" array. The MOEs and DTOC are stored in two separate locations. They are first stored exactly as calculated. They are then stored with a penalty applied if the components of the vehicle are too long or too heavy. If the vehicle is feasible, then no penalty is applied. The penalty applied changes with the number of the generation. For the first 20% of the generations, no penalty is applied (Penalty = 1). Over the next 60% of the generations, the penalty is increased to 10. Between 80% and 100% of the generation, the penalty is the maximum value of 1,000,000. (See Figure 4-9) The penalty is applied to DTOC and HAMOE by multiplying the calculated value by the penalty. For HD/F CMOE, the calculated value is divided by the penalty. After each generation, the population array objective attributes are updated with the current generation penalty.

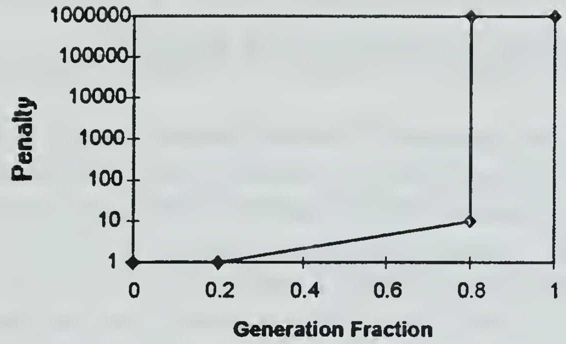

Figure 4-9 Population Objective Attribute Penalty as a Function of Generation

The penalty is small in early generations to allow the genetic information from members that have favorable characteristics but infeasible designs to be retained in the population. The final generations, however, contain only feasible designs to maximize exploitation. For this reason the penalty is very large near the end so that only feasible designs are allowed to continue as parents.

4.9.4 Non-Dominated Designs

As the potential solution space is searched, each member generated is compared to all previously discovered non-dominated solutions stored in the "non_dom" array. If the member is too long or too heavy, then DTOC, HAMOE and HD/F CMOE are all set to 1,000,000 to ensure that the member will always be rejected from the non-dominated array. DTOC, HAMOE and HD/F CMOE for the new member are then compared to each member in the non-dominated array. If the new member is not strictly dominated by any member currently stored in the array, (i.e. no member of the array performs better in all 3 objective attributes) then the new member is placed in the array. If the new member performs equally well to a current member of the array, then a check is

performed to determine if the new member is a clone. If it is a clone, it is rejected. If, however, it is a different design with identical performance, it is placed in the array. A check is then performed to determine if the new member strictly dominates any current members of the array. If the new member performs better in all 3 objective attributes to any other individual, then that individual is removed from the array.

The non-dominated array differs from the population array in that "non-dom" maintains all of the non-dominated solutions found throughout the entire process. The population array only contains the current genetic information being used by the algorithm.

4.10 Display of Information

Once the non-dominated array is complete, it is displayed graphically on a plot with HD/F CMOE on the horizontal axis and HAMOE plotted on a log scale on the vertical axis. Different DTOCs are represented on different curves with colors or shapes changed. The decision-maker is then able to determine the appropriate level of spending to obtain the desired effectiveness in hydroacoustics and hydrodynamics / flexibility.

Without knowing the answer to the problem beforehand, it is very difficult to determine when the Pareto frontier is complete. Typically the algorithm is run for a specific amount of time or until there is a specified improvement rate in the non-dominated array.

5
Tuning the Genetic Algorithm

Once the evolutionary program has been developed, the parameters of the genetic algorithm must be adjusted to optimize search performance. The design evaluator for LSV II is fast enough that an exhaustive search of all possible designs can be performed and used to tune the genetic algorithm. This thesis refers to the complete process as the evolutionary program and the specific parts dealing with selection and mating as the genetic algorithm.

5.1 Exhaustive Search

Initial data runs of the evolutionary program indicated that the entire space could be searched in a reasonable amount of time. An exhaustive search is often not feasible in design problems because of the amount of time required to perform an evaluation of the large number of possible design alternatives. An evaluation of each LSV design requires approximately 0.01 seconds on a 133 MHz Intel Pentium Processor using 16 MB of RAM. The initial design parameter space includes 4.2 million possible combinations, so the entire space can be searched in just over 12 hours.

An exhaustive search was performed to determine the Pareto frontier for the initial design space. The exhaustive search data was used to fine-tune the genetic algorithm. The complete set of non-dominated designs was compared to the non-dominated designs found using the evolutionary program to obtain a metric for performance of the evolutionary program. The exhaustive search data was also used to analyze trends in objective attribute space and evaluation of design parameter limits.

5.1.1 Exhaustive Search Method

The exhaustive search is conducted by sequentially stepping through each combination of binary elements in the chromosome. Each chromosome is then decoded and evaluated for feasibility, performance, effectiveness and cost. The process is identical to selection of the initial population in the genetic algorithm, but instead of random selection, the process is structured and exhaustive (See Figure 5-1.)

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Figure 5-1 Exhaustive Search Chromosomes

5.2 Tuning the Genetic Algorithm

Many of the parameters within the genetic algorithm can affect its performance. The following are investigated in this thesis:

Generation Size.

Mutation Rate.

Penalty for infeasible designs.

Restart of many short runs or use of one long run.

Each of the above parameters is separately varied while all other parameters in the genetic algorithm are held constant. The results are compared to the exhaustive search to determine their effect on the performance of the evolutionary program.

5.2.1 Generation Size

Generation sizes of 150, 200, 250, 300 and 350 are compared in an attempt to determine the optimum generation size. The generation size sets the initial number of members in the population. A new generation is finished when the number of children created in that generation equals the generation size. Increasing the generation size introduces more genetic information into the algorithm, but also requires more computer time per design evaluation. Time to complete each evaluation is an exponential function of the generation size. (See Figure 5-2)

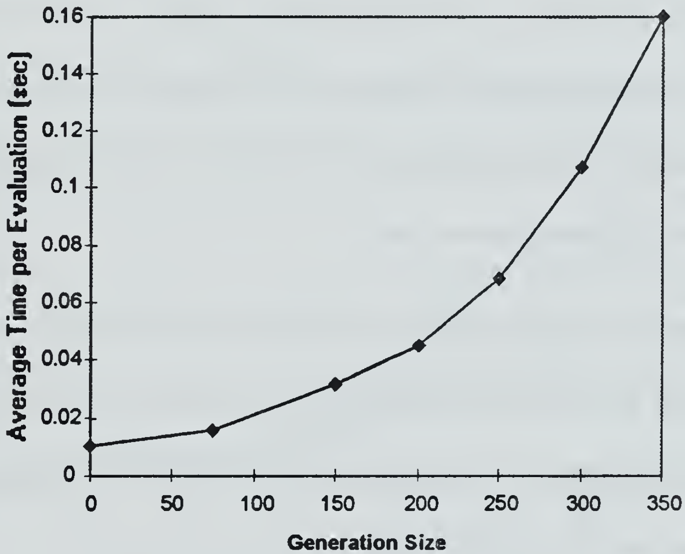


Figure 5-2 Average Time per Evaluation as a Function of Generation Size

In this particular problem, the time to evaluate each design is on the same order of magnitude as the time to perform the genetic algorithm. The difference between the 0.03 seconds required for a generation size of 150 and the 0.16 seconds for a generation size

of 350 is significant. In the case of a more complicated problem, where the time to evaluate each design requires several orders of magnitude more time than the genetic algorithm, however, this time difference is insignificant. Because this thesis is attempting to show the possible effects of this method on full scale ship design, the time required for genetic algorithm processing is ignored. For this reason, all comparisons are made with number of evaluations required rather than amount of time to required to execute the program.

Figures 5-3 and 5-4 indicate that in general, more non-dominated designs are found more quickly with a larger generation size. The line labeled as random shows the expected rate of finding non-dominated designs using a random search of the design space. The smaller the slope of these curves the better the performance of the search. When compared with the random search, all of the evolutionary programs perform well no matter which parameters are used.

Figure 5-3 shows only the evolutionary program results. It can be seen that early in the process there is little difference in the performance of different generation sizes, and in several places, the curves actually cross. At the end of the plot, however, the larger generation sizes perform better.

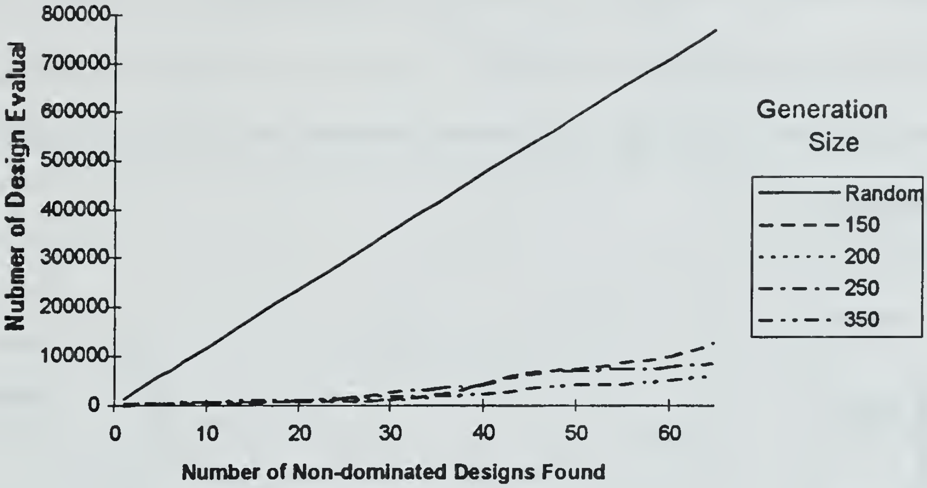


Figure 5-3 Program Performance with Varying Generation Size Compared to Random Search

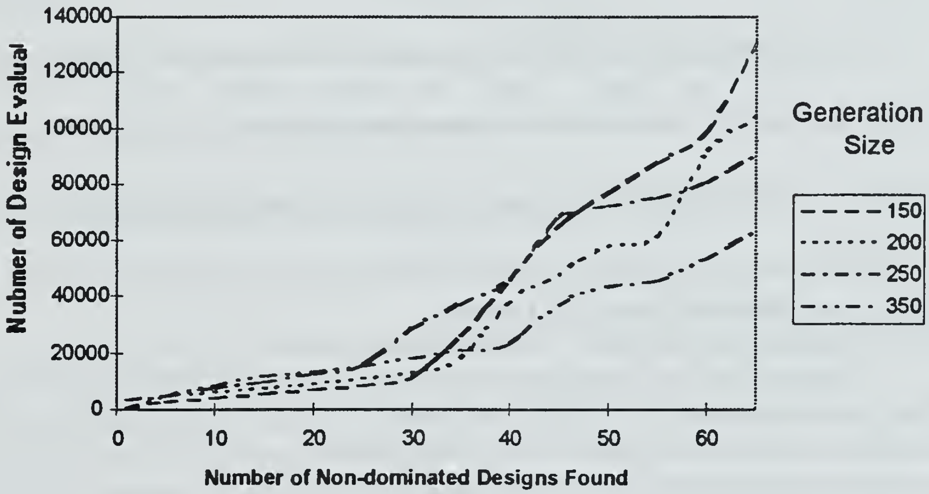


Figure 5-4 Program Performance with Varying Generation Size

5.2.2 Mutation Rate

Mutation rate is varied between 0.1 and 0.001. The first run uses a mutation rate that starts at 0.1 for the initial generations and ends at 0.001 for the final generations. The second run starts at 0.1 and ends at 0.01. The other three runs all use constant

mutation rates. (See Figure 5-5) The best performer based on this limited number of runs is the constant mutation rate of 0.01. At this rate, one digit is flipped on average about once every 4 offspring. The constant mutation rate of 0.01 is used for all further evaluations.

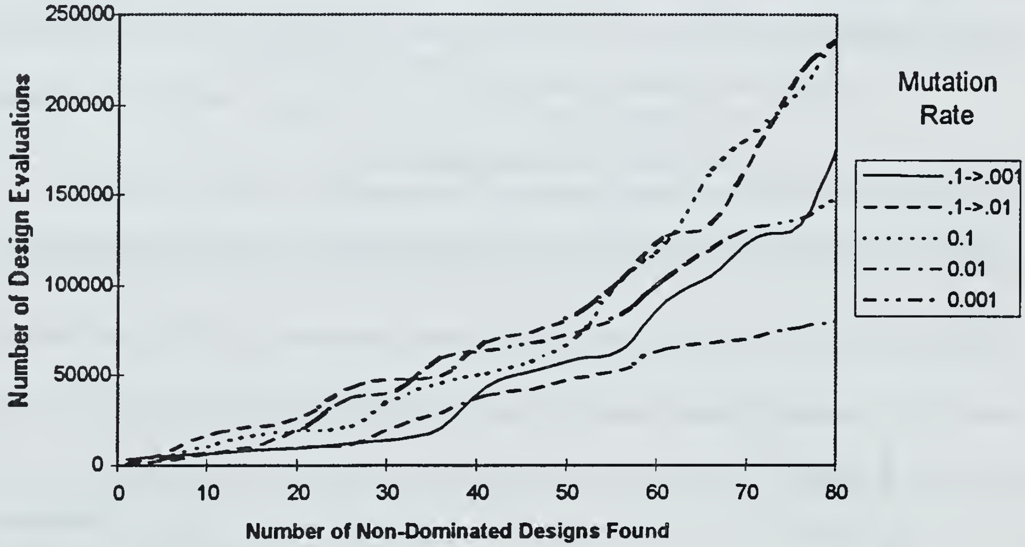


Figure 5-5 Program Performance with Varying Mutation Rate

5.2.3 Penalties for Infeasible Designs

Designs that are infeasible are allowed to remain in the population with their calculated objective attributes during early generations and are heavily penalized in later generations. Figure 5-6 indicates the gain in algorithm performance seen by applying this variable penalty scheme. Allowing genetic information from infeasible designs with desirable characteristics has positive effects on the algorithm.

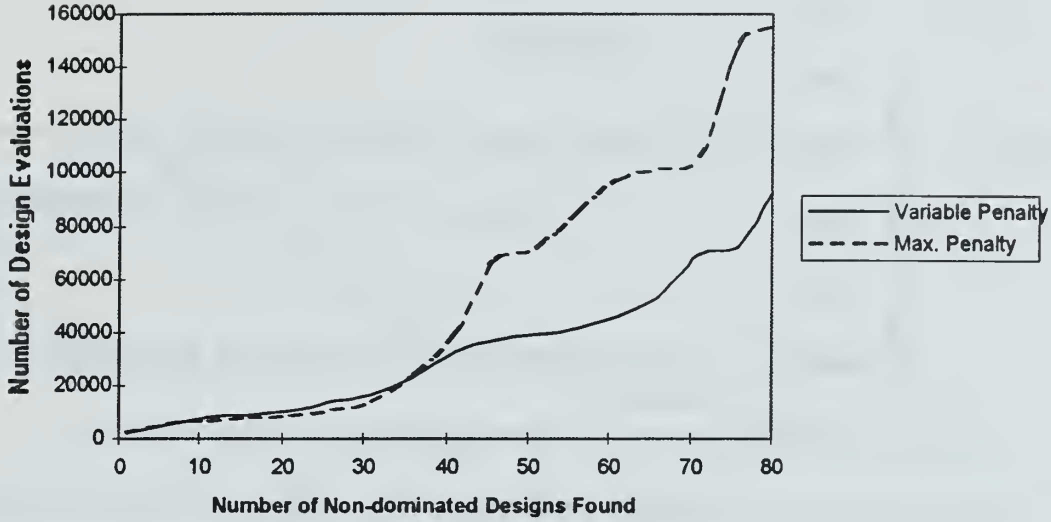


Figure 5-6 Program Performance with Varying Population Penalties

5.2.4 Restart

A comparison is made between restarting the genetic algorithm after 150 generations and allowing the algorithm to run continuously. Both methods appear to work equally well in this application. Two separate comparisons are made. In one case, the restart option works better and in the other case the continuous run works better. (See Figure 5-7.) Each method has benefits and drawbacks. The continuous run option allows refining of a population that is known to have good designs. It introduces new genetic information by mutation and maximizes exploitation. The restart option accepts the performance of a population after 150 generations and then starts over with a new set of random genetic information, maximizing exploitation.

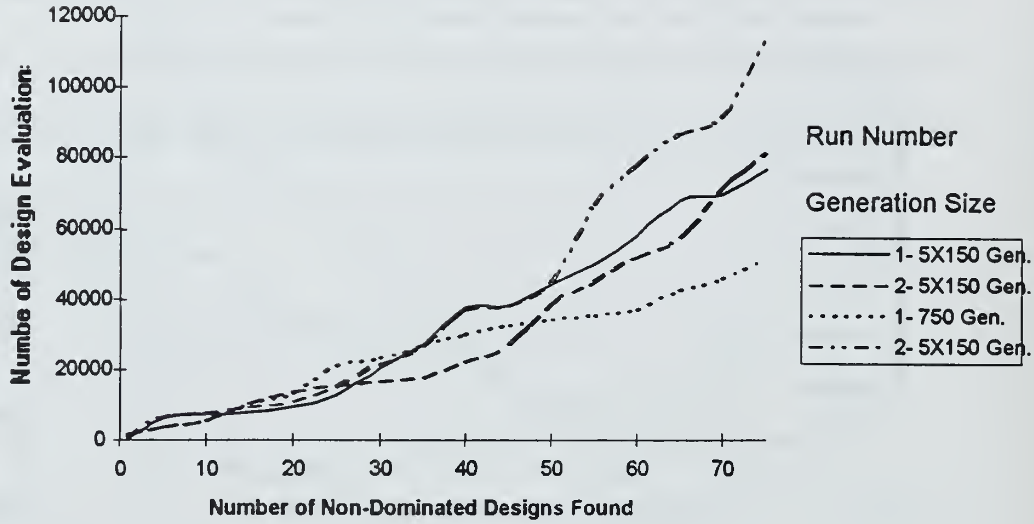


Figure 5-7 Program Performance Comparing Restart vs. Large number of generations

5.3 Conclusion

The analysis of varying the parameters of the genetic algorithm indicates the evolutionary program is very robust and works well over a wide range of parameters.

6
Results

Chapter 6 discusses the specific results obtained from the evolutionary program applied to the design of Large Scale Vehicle II.

6.1 Objective Attribute Trends on the Pareto Frontier

An analysis of the Pareto frontier generated from the exhaustive search is discussed in this section. Figure 6-1 is a plot of the Pareto frontier for selected costs. Appendix B contains the complete plot and the characteristics of each design found by exhaustive search. The non-dominated designs tend to congregate in 5 different regions. The regions are represented by ovals on the Pareto frontier plot of the exhaustive search.

6.1.1 Pareto Frontier Plot Explanation

The vertical axis of Figure 6-1 represents the hydroacoustic measure of effectiveness (HAMOE). It is plotted on a logarithmic scale because it represents an acoustic uncertainty band that is measured in decibels. The horizontal axis represents hydrodynamic and flexibility combined of effectiveness (HD/F CMOE), which is based on an expert opinion combination of geo-similitude, number of Froude scale maximum speed runs (FSRs) and margin. The base score for HD/F CMOE is the design's margin, and additional credit is given by the MAIE method for improvements above the threshold in geo-similitude and number of FSRs. It is plotted on a linear scale because it is closely related to margin, which is represented well with a linear display. The negative value of HD/F CMOE is plotted so that all objective attributes are better as low values. In this

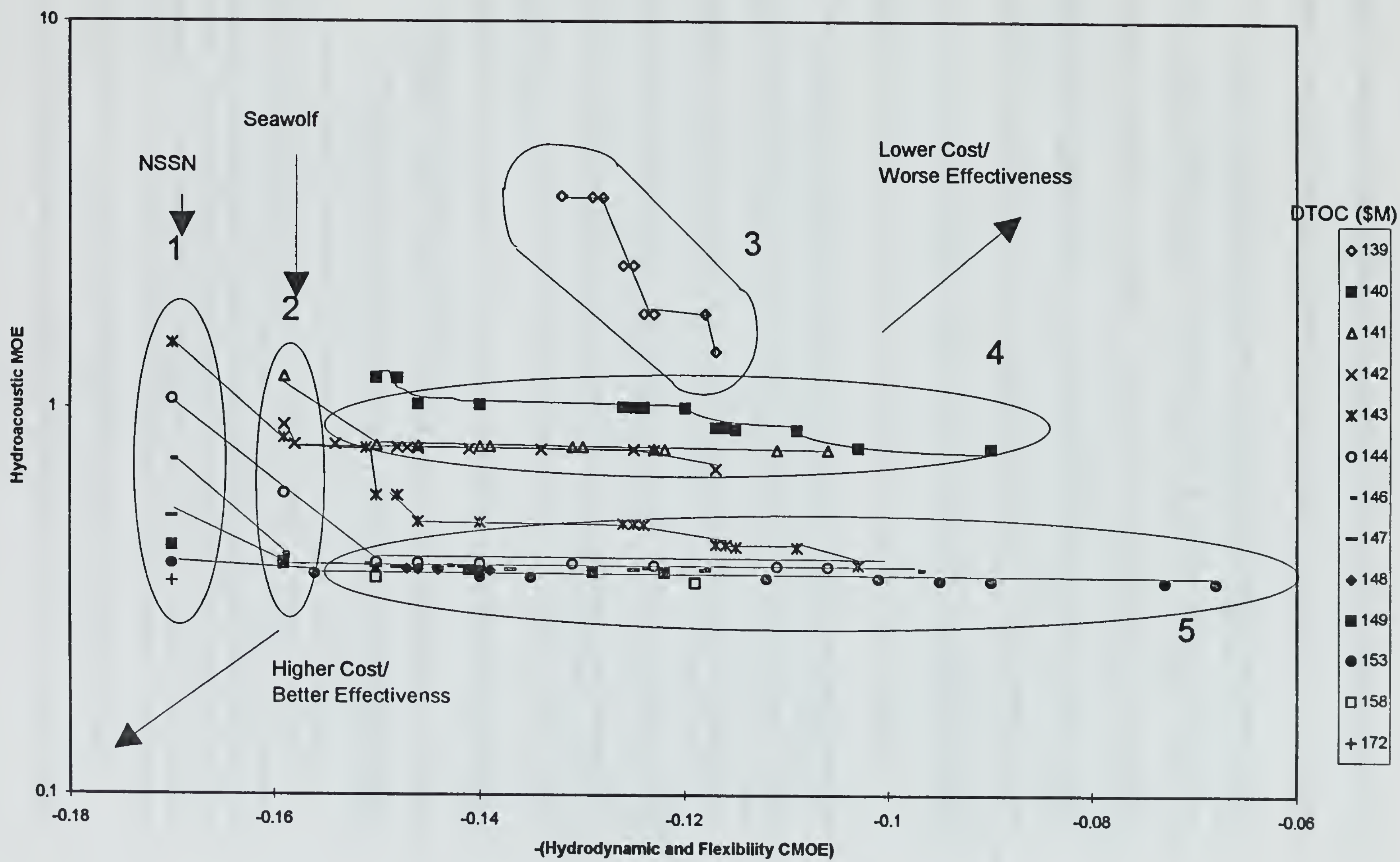
way the algorithm attempts to minimize all 3 objective attributes rather than minimizing some while maximizing others.

Each different symbol represents a different discounted total ownership cost (DTOC) in millions of dollars. On Figure 6-1, all designs with a common DTOC are connected with a constant cost line. Each design that was found by the exhaustive search to be non-dominated is represented by a symbol on the plot. The type of symbol represents its DTOC and its location on the plot represents its HAMOE and HD/F CMOE. The least effective and least expensive variants are located in the upper right hand corner of the plot, and the most effective and most expensive variants are located in the lower left hand corner of the plot.

6.1.2 Pareto Frontier: Exhaustive Search

This section explains the reasons for the groupings on the Pareto frontier found by exhaustive search. The numbered regions in the following discussion refer to the oval regions on Figure 6-1.

Figure 6-1 Pareto Frontier: Exhaustive Search



All designs on Figure 6-1 exceed the goal in number of Froude scale runs and therefore receive the maximum increase in HD/F CMOE allowed for number of FSRs. This is because all variants that perform well enough to attain a reasonable HAMOE also perform well in number of FSRs due to their better endurance at higher speeds. At the margin goal of 12%, the increase in score is 0.03. Therefore, a design with margin and FSRs at the goal values attains a HD/F CMOE of 0.15 without geo-similitude of New Attack or Seawolf. (Extreme left side of Regions 4 and 5.) The only way to achieve a better score than 0.15 is with geo-similitude. (Regions 1 and 2.)

Regions 1 and 2 are areas of increased hydrodynamic performance due to geo-similitude (geo-sim). Region 1 contains all of the New Attack geo-sim variants and Region 2 contains most of the Seawolf variants. Since New Attack is the preferred geo-sim, it attains the highest scores for HD/F CMOE (an increase of 0.02 with margin and FSRs at the goal) . The New Attack is "long and thin", but has relatively high resistance, which leads to poor performance in maximum speed and endurance. There is no New Attack geo-sim on the Pareto frontier below the HD/F CMOE score 0.17. The Seawolf geo-sim has better resistance characteristics than the New Attack, but not as good as many of the other variants in the design space. The maximum HD/F CMOE for a Seawolf variant is 0.16. Between 0.15 and 0.16 are only Seawolf variants.

Region 3 contains the least expensive variants. All of the designs in this region have minimal hull coating and the baseline sonar system. This is the least expensive method to build the LSV II, and hence produces the designs with the worst effectiveness.

Region 4 contains the designs with moderate effectiveness. All of the variants within this region have either maximum hull coating and the baseline sonar system, or

minimal coating and the upgraded sonar system. The compromise on design parameters yields the middle of the road effectiveness and relatively low cost.

Region 5 contains the majority of the non-dominated designs. All of the designs in this region have the maximum hull coating and upgraded sonar system. This region of the Pareto frontier is very nearly flat because the hull coating thickness is at its maximum allowed value. The only way to improve HAMOE is to increase the vehicle maximum speed, but at the high speeds, the powering curve is very steep. To increase vehicle speed by even a small fraction requires a large amount of margin to be sacrificed for additional batteries.

The design with the best effectiveness and highest cost in the design space is plotted in the lower left hand corner. It is a New Attack geo-sim with upgraded sonar system and maximum coating. It has high maximum speed at 36.9 knots due to its advanced battery (Nickel-Zinc) and high battery power. It has the highest battery power rating at 5100 kWe of any non-dominated design. It also has the highest acquisition cost at $59.2 million.

6.1.3 Margin as a Measure of Effectiveness

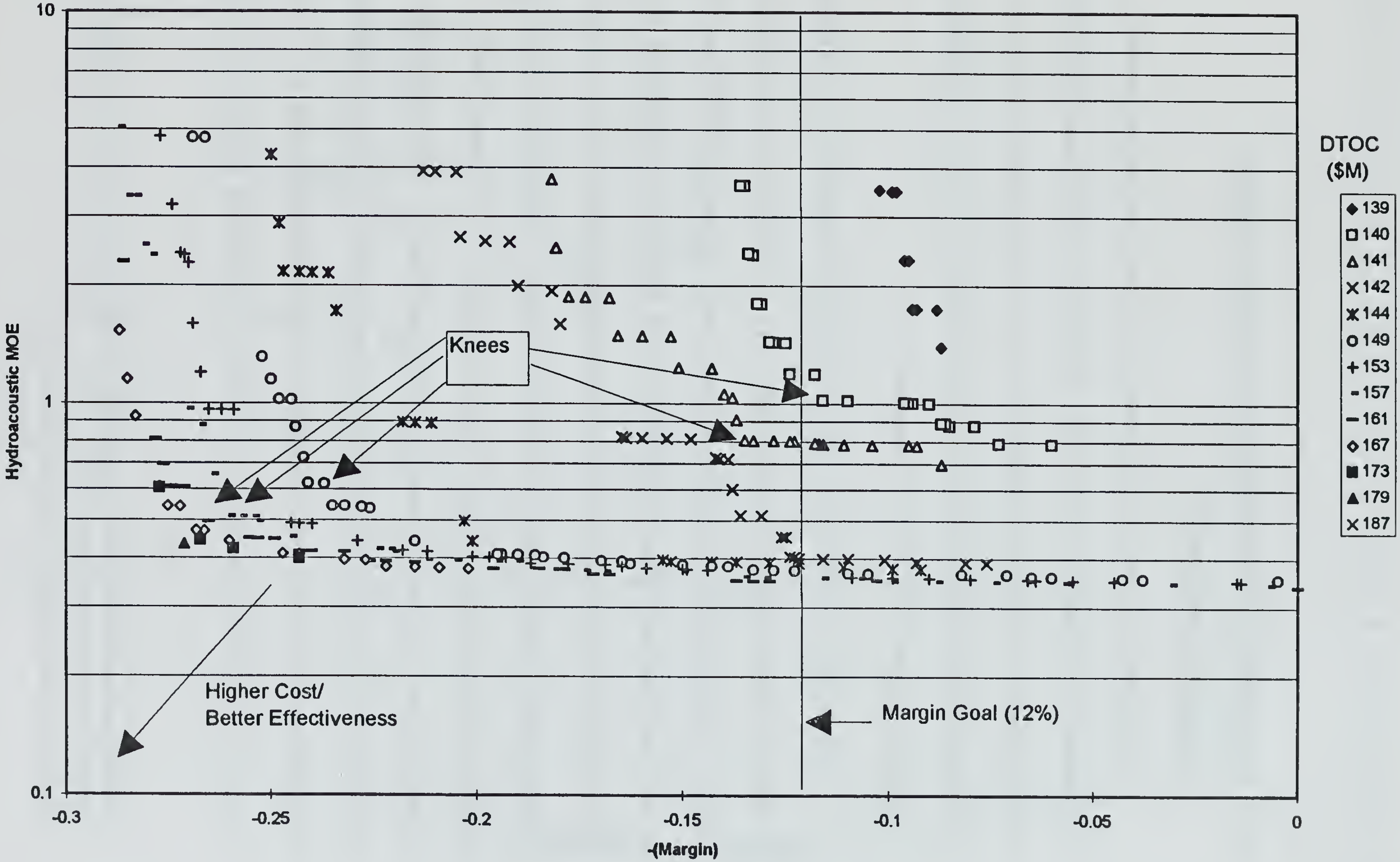
There are very few gradual changes in the Pareto frontier, primarily because of the goals and thresholds selected for measures of performance, the limits placed on design parameter space and the method used to determine HD/F CMOE. To illustrate this point, the exhaustive search was repeated, but instead of using the expert opinion HD/F CMOE, only margin was used as the measures of effectiveness. A representative

sample of the Pareto frontier with margin is presented in Figure 6-2. Many of the sets of DTOC points were eliminated for ease of presentation.

Most of the cost curves to the left of the margin goal of 12% have a knee before they approach the margin goal. The left end of each curve (poor HAMOE and best margin) represents slow vehicles that have minimal coating and the baseline sonar system. The steep part of the curve is created because a small increase in coating provides a relatively large improvement in HAMOE. At a certain point, it becomes more cost effective to upgrade the sonar system instead of increasing coating thickness. At that point, a shift is made from maximum coating thickness to minimal coating thickness with upgraded sonar system. Improvement in HAMOE then comes from increases in coating thickness. As coating thickness increases, speed of the vehicle drops off because of increased resistance. When the maximum thickness allowed is reached the only method available to improve HAMOE is to increase the vehicle maximum speed by lowering resistance or increasing power. Reducing the hull size decreases resistance; increasing battery size increases power. Both methods require sacrificing large amounts of margin, which causes the shallow part of the curve.

Another interesting point about the margin Pareto frontier is there are no Seawolf or New Attack variants on this frontier. All Seawolf and New Attack variants are dominated. Since all variants found by the exhaustive search have goal performance in FSRs, it is clear that the only reason variants with geo-similitude are on the frontier for HD/F CMOE is because of the added value directly attributed to geo-similitude.

Figure 6-2 Partial Pareto Frontier: Exhaustive Search w/ Margin as MOE



6.2 Comparison of Evolutionary Program Search to Exhaustive Search

This section evaluates the effectiveness of an evolutionary program search by comparison to the exhaustive search results. Evolutionary program results using a 200-member population and 40 generations (8,000 evaluations) are presented in Figure 6-3. The results from this same population extended through 80, 120 and 160 generations are presented in Figures 6-4, 6-5 and 6-6 respectively.

After 8,000 evaluations of the 4.2 million possible designs (Figure 6-3) the basic shape of the Pareto frontier can be seen in the 147 potentially non-dominated designs found.[3] When compared to the exhaustive search results, the range of DTOC and MOEs is very closely predicted, although only 18 of the 295 absolutely non-dominated designs have been found.[4] (See Table 6-1 for non-dominated design totals.) Regions 1 and 5 from the exhaustive search are very closely approximated. Although not all of the points are present, the trend of the curves in these two regions is nearly identical to the exhaustive search. Region 3 from the exhaustive search contains only designs with a DTOC of $139M. Two of these designs were found with the evolutionary program, and the remainder of the $140M points approximates the rest of region 3 fairly well. Region 4 has very few points and no trend can be obtained from the data. Region 2 has no points

[3] A potentially non-dominated design is one found by the evolutionary program. There may be other designs that dominate it, but have not yet been found.

[4] An absolutely non-dominated design is one found by exhaustive search.

Figure 6-3 Pareto Frontier Estimate (8,000 evals)

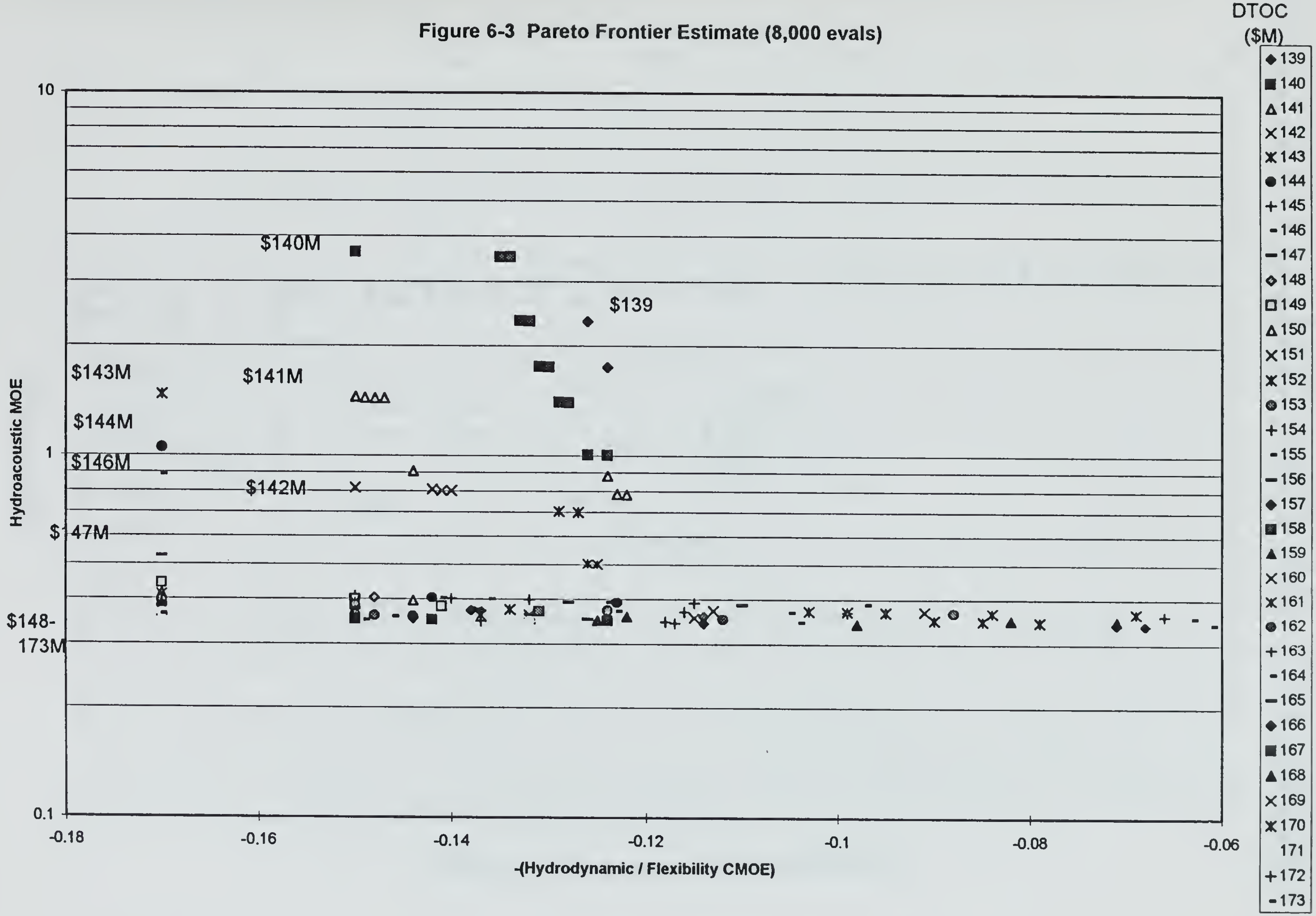


Figure 6-4 Pareto Frontier Estimate (16,000 evals)

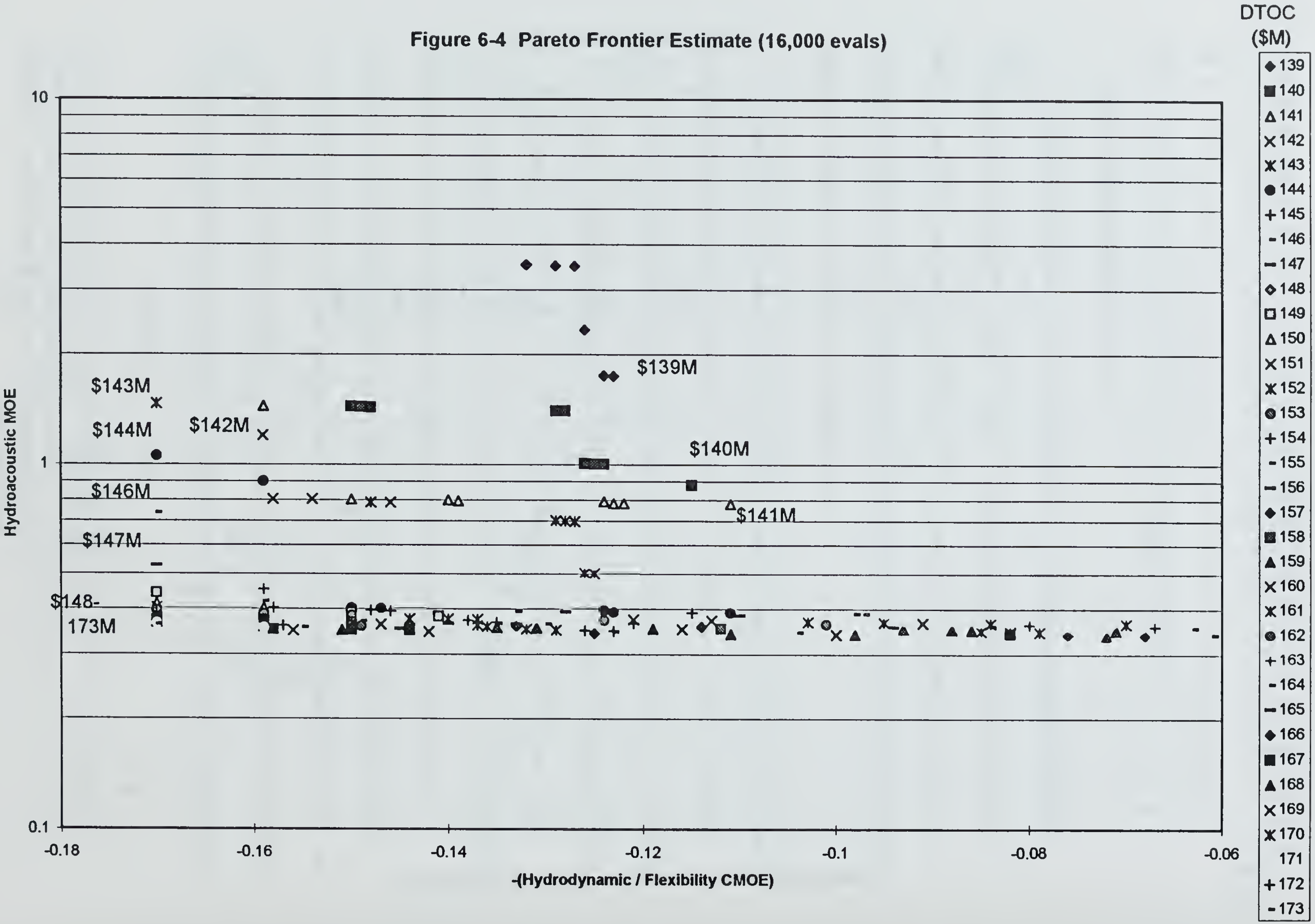


Figure 6-5 Pareto Frontier Estimate (24,000 evals)

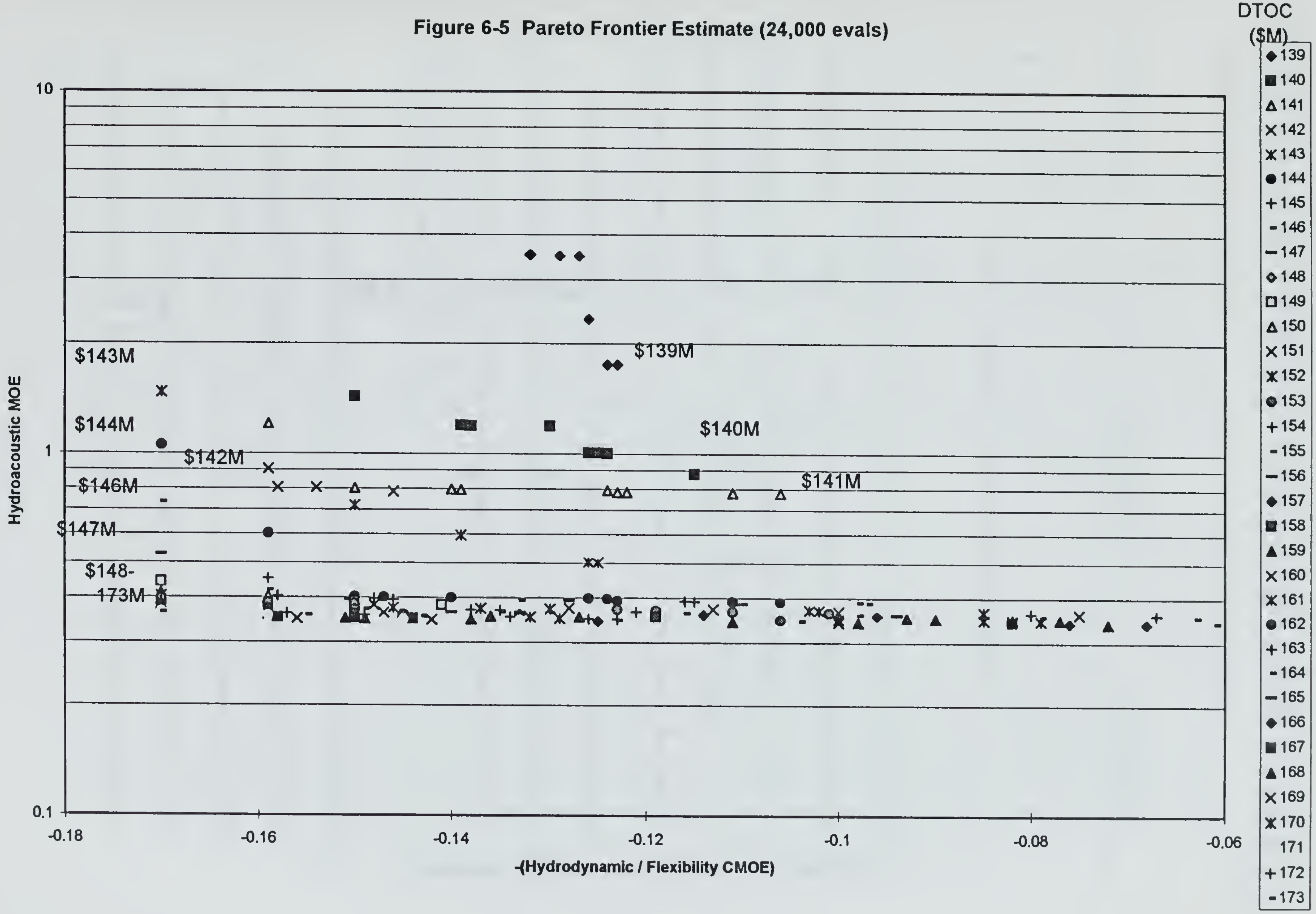
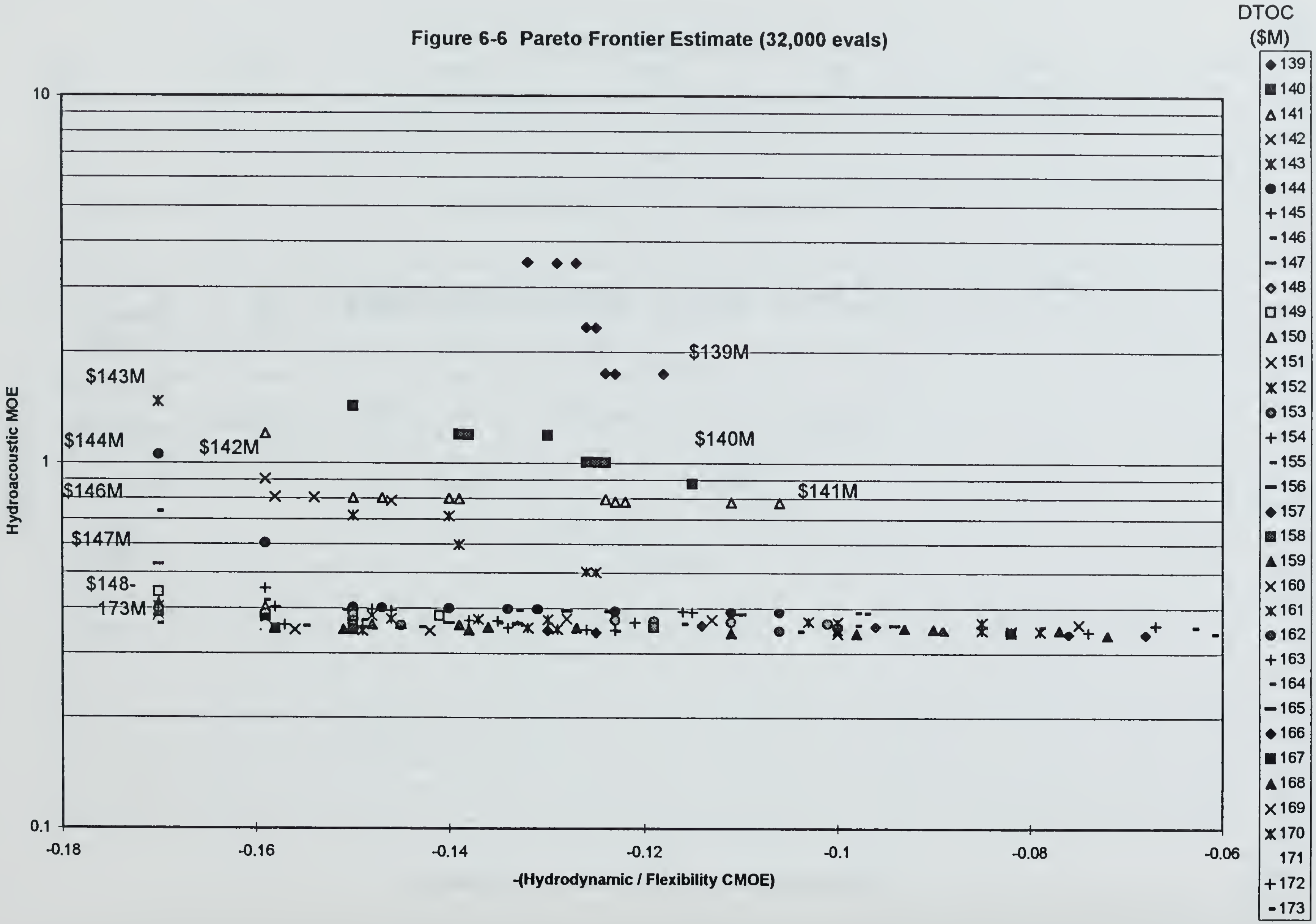


Figure 6-6 Pareto Frontier Estimate (32,000 evals)



whatsoever. At this point the program has not yet found any of the designs with Seawolf geo-similitude.

Generation Number	Potentially Non-Dominated	Absolutely Non-Dominated
40	147	18
80	176	36
120	191	48
160	198	58

Table 6-1 Evolutionary Program Performance Summary

After 16,000 evaluations (80 generations, Figure 6-4), Regions 1 and 5 obtain even better definition. Region 3 is now very well defined with the exception of the very best hydroacoustic performers. Region 4 has slightly better definition, but is still somewhat under represented. Region 2 shows the best gains. This region is now very well defined, missing only a few representative points near the center of the region.

After 24,000 evaluations (Figure 6-5), Regions 2 and 4 obtain better definition with more points closer to absolute non-dominated points. Very little difference can be seen in the other regions. After 32,000 evaluations, further definition is obtained in Region 4 that indicates the actual trend.

Figure 6-7 represents the performance of the algorithm. The curve labeled "Tot Add" is the total number of designs evaluated and placed in the non-dominated array. The curve labeled "Tot Remove" is the total number of designs removed from the non-dominated array because they are dominated by a newer design. "Non-Dom" is the difference between "Tot Add" and "Tot Remove" and represents the total number of

designs in the non-dominated array. "Absolute Non-Dom" represents the number of non-dominated designs from the exhaustive search found by the evolutionary program.

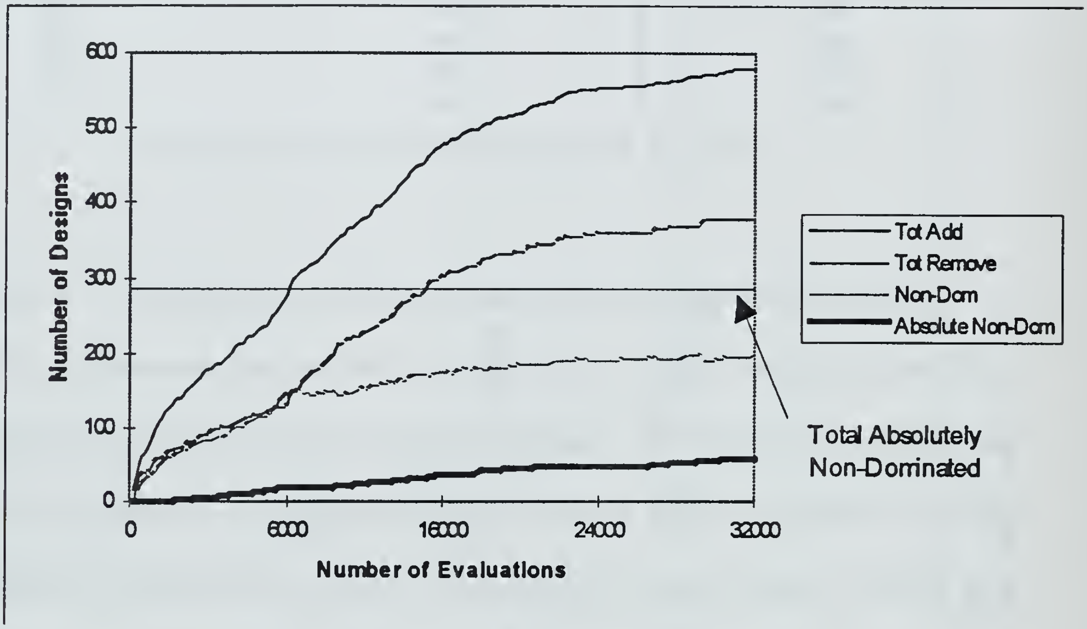


Figure 6-7 Evolutionary Program Performance

During the initial generations, the number of non-dominated solutions increases rapidly because the number of previously found designs is small. As more non-dominated designs are added, the rate of finding new non-dominated designs drops off. The number of absolutely non-dominated designs behaves in a similar manner, but is not as pronounced. The marginal gain in conducting further evaluations continues to drop off as more designs are evaluated. Even though only a small fraction of the absolutely non-dominated designs have been found (20% after 160 generations) the extents and trends in

attribute space are very well defined. The algorithm has found a large number of designs that very closely approximate the absolutely non-dominated designs.

6.3 Expanding the Design Parameter Space

There are many discontinuities in the exhaustive search Pareto frontier. The exhaustive search does not provide a continuous plot for two reasons. First, the continuous parameters are approximated as discreet. The larger the distance between the discreet values, the larger the distance between the points in effectiveness space. Second, even if all continuous parameters were modeled to a high precision, there are still 2 parameters that are by their very nature discreet: sonar type and battery type. To reduce the distance between the points on the Pareto frontier, the number of binary digits in each continuous gene is increased by one in the next phase of the search.

If the minimum and maximum values for design parameters are improperly chosen, the solution space can be arbitrarily constrained. In this problem 29% of all non-dominated variants have a battery power at the minimum value and only dominated variants have hull diameters less than 10 feet. This indicates that the low end of battery power was improperly chosen, arbitrarily constraining the solution to the larger hulls that can support the larger battery power requirements. In addition, only dominated solutions have battery power greater than 5100 kWe, indicating that the maximum battery power of 6500 kWe is too high. The battery power range is lowered for the next phase of the search.

A similar phenomenon occurred with coating thickness. Of all non-dominated designs, 86% have the maximum coating thickness allowed. This again indicates that the

maximum coating thickness may have been improperly chosen. The maximum coating thickness is increased for the next phase of the search.

6.3.1 Expanded Search

Valuable insight is gained by having a problem small enough to use an exhaustive search, but even a small problem rapidly becomes large if the number of design combinations is increased to shrink the gaps in the Pareto frontier. In this problem, the length of each gene representing a continuous variable is increased by one. This increases the number of possible combinations by a factor of 64. The time required to run an exhaustive search for this case is nearly one month. The new gene sizes are provided in Table 6.2.

	Gene Size	
	Old	New
D	3	4
L/D	3	4
N_f	3	4
N_a	3	4
Battery Type	2	2
Battery Power	4	5
Hull Coating Thickness	3	4
Lake Sonar Type	1	1
Total Chromosome Size	22	28
Possible Designs	4.2 Million	268 Million

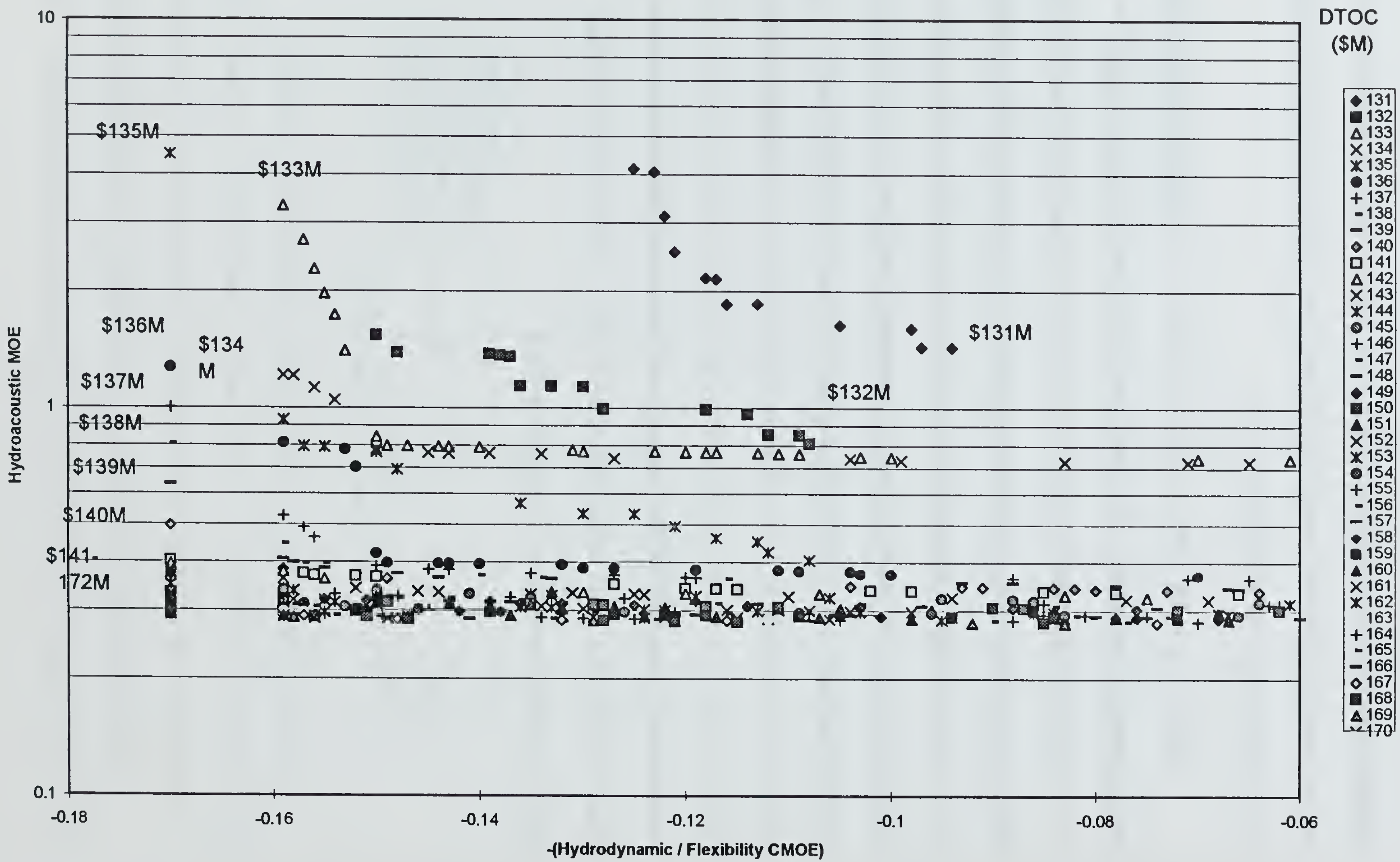
Table 6-2 Gene Sizes for Revised Model

The search is also expanded in range of design parameter values allowed for battery power and coating thickness. Battery power is now allowed to vary from 1500 to 5500 kWe at the 5-minute rating. This allows the smaller hull sizes an opportunity to generate feasible designs. Coating thickness is allowed to vary between 0.0 and 4.5 inches. Allowing thicker coating eases the knee in the curve of the Pareto frontier. This

maximum thickness is at the limit of the allowable thickness. If thicker coating is applied, new analysis of the coating cost function must be conducted. The available data is for relatively thin hull coatings only. [23]

Figure 6-8 is a plot of the evolutionary program Pareto frontier with the expanded design parameter search space. The basic shape of the frontier is very similar to the frontier found with the exhaustive search. All 5 regions represented on the exhaustive search plot are also present on the expanded search plot. The primary difference is the improvement of HAMOE in region 5 and the shifting of the DTOC to lower values. Region 5 shifts to better values of HAMOE because the maximum thickness of the coating is increased to 4.5 inches. This improves the maximum hydroacoustic effectiveness of the vehicle. The DTOCs are lowered because of the lowering of the minimum battery power. This allows smaller hulls, which cost less, to be feasible. There are other minor changes in the plot, but the general shapes and locations are the same. Because the precision of the design parameters is higher, the non-dominated design points are closer to each other on the Pareto frontier.

Figure 6-8 Pareto Frontier Estimate: Expanded Search

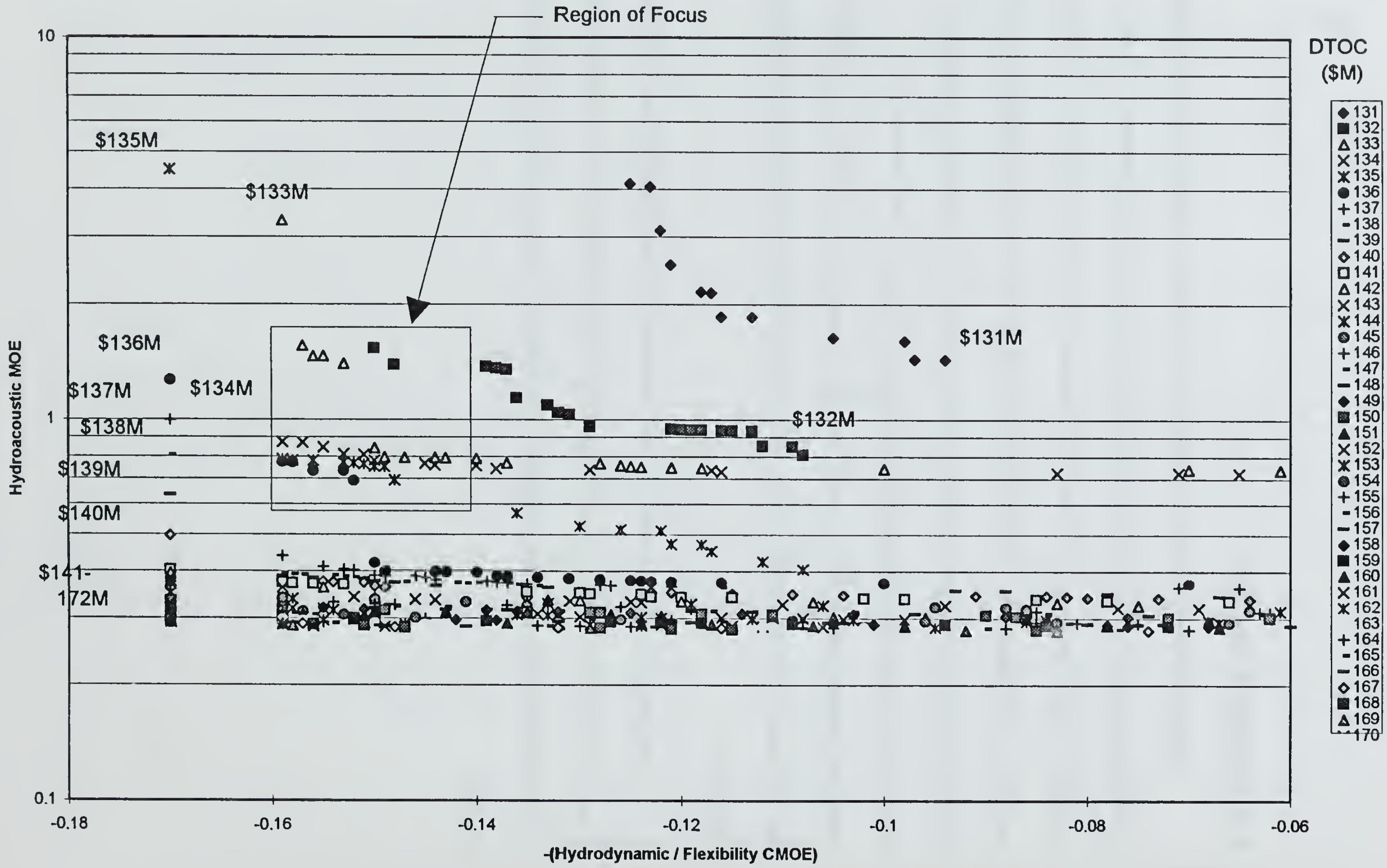


6.4 Focused Search

There are areas on the expanded search plot where the separation between points is larger than desired. For example, the area bounded by HAMOE between 0.6 and 1.7 and HD/F CMOE between -0.16 and -0.14 appears to contain several knees in curves and has fairly wide separation. To focus in on this region, all the points within the region are analyzed separately from the remainder of the frontier. The minimum and maximum values of the design parameters within this region are used as the minimum and maximum design parameters for a new search. The search starts with the non-dominated designs found in the expanded search. The results of this focused search are presented in Figure 6-9.

The area of the focused search now has a much higher density of non-dominated points. The frontier in this region has also improved, especially for those designs with a DTOC of $133 million and $134 million. The frontier for these costs has improved HD/F CMOE.

Figure 6-9 Pareto Frontier Estimate: Focused Search



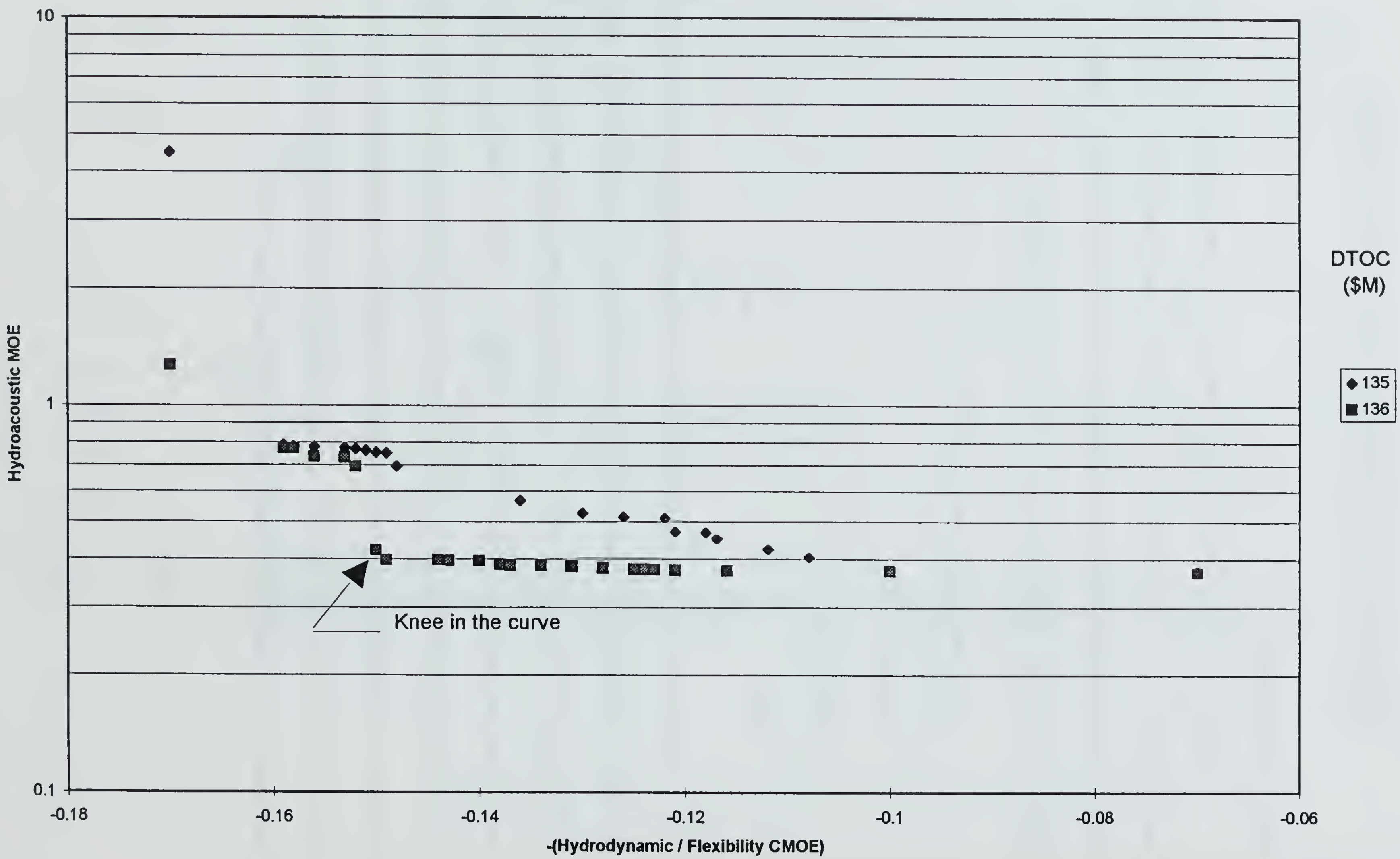
6.4.1 Final Decision

Any of the variants on the focused search plot are non-dominated when compared with all of the other evaluated designs. The decision-maker can choose any of them and feel confident that the design is very close to the actual Pareto frontier. Several approaches are used in combination to determine the final design:

1. Cost as an independent Variable (CAIV)
2. Knee in the curve
3. Thresholds
4. Goals

If cost is truly an independent variable in the decision process, then all designs that do not cost the predetermined value can be eliminated. For example if the initial CAIV target were set to $136 million, then the best choice may be the location of the knee in the curve at (HD/F CMOE = 0.149, HAMOE = 0.398). (See Figure 6-10) CAIV does dramatically simplify the decision process, but it also ignores valuable data. For example, if $135 million is chosen as the CAIV target, then a relatively large gain for an investment of $1 million is ignored. For an additional $1 million HAMOE can be improved by 0.35 while maintaining HD/F CMOE at 0.149.

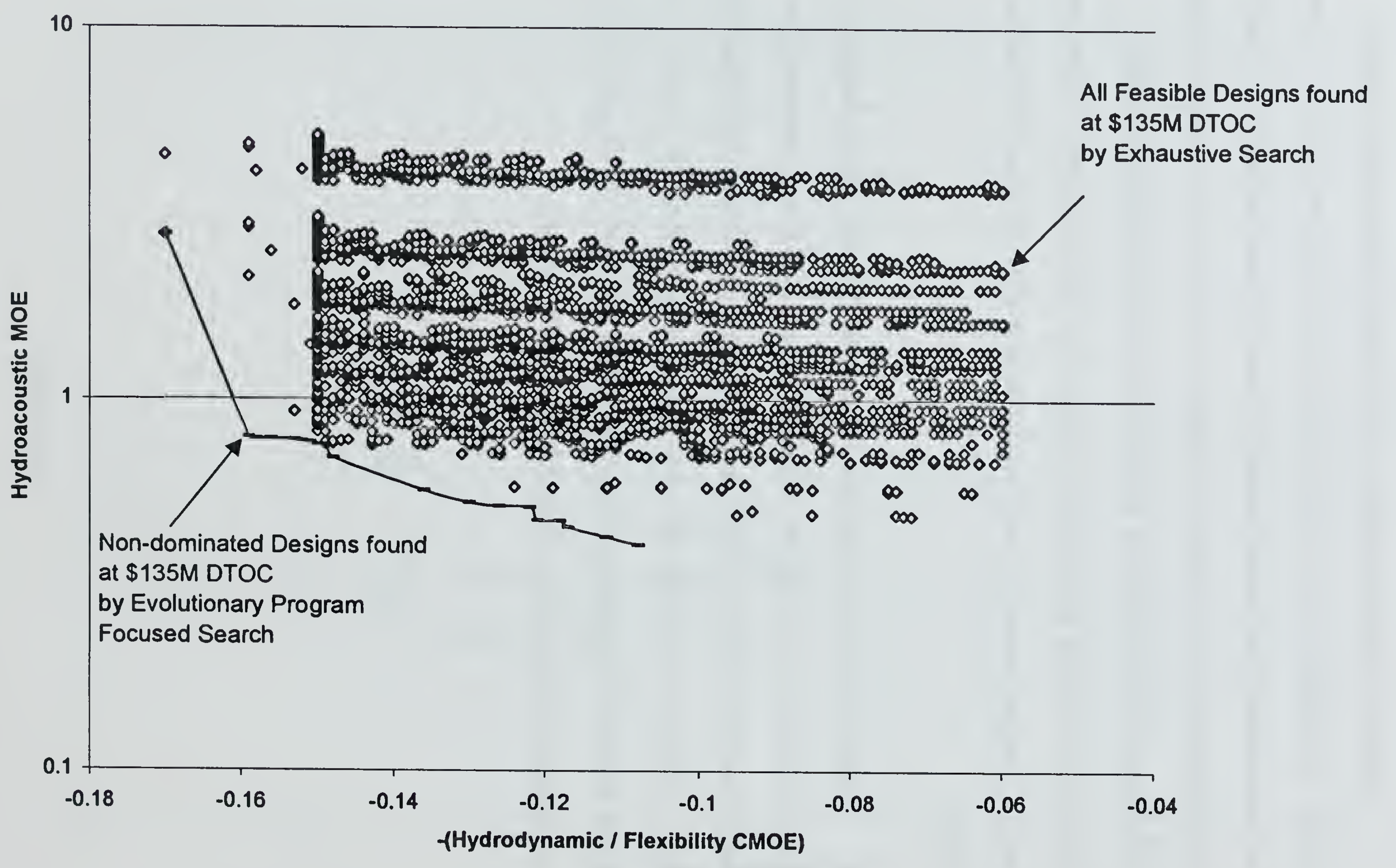
Figure 6-10 Partial Pareto Frontier Estimate: Focused Search



Goals and thresholds are better means of bracketing the decision process if needed. For example, it may be decided that HAMOE should be less than 0.8 to ensure that the uncertainty band is small enough for proper propulsor evaluation. Setting the HAMOE threshold at 0.8 eliminates all designs above this value. The decision of goal and threshold for HD/F CMOE is actually one of what geo-similitude is desired. To achieve a HD/F CMOE greater than 0.15, Seawolf or New Attack geo-similitude must be used. All designs between 0.15 and 0.16 are Seawolf while all those at 0.17 are New Attack.

If geo-sim is not very important, then the best choice may be the design at the knee in the curve for $136 million. If Seawolf geo-sim is important, then any of the designs with HD/F CMOE at 0.16 is the appropriate choice because of the flatness of the curve in this region. The trade-off in this situation is strictly HAMOE vs. DTOC. If New Attack geo-sim is important, then any of the designs with HD/F CMOE equal to 0.17 is appropriate and a direct trade-off of HAMOE vs. DTOC is used.

Figure 6-11 All Feasible Designs at $135M



The important aspect of this decision process is that there are no wrong decisions on the Pareto frontier. This can be seen on Figure 6-11. Each diamond represents a feasible design of DTOC $135M found by exhaustive search using the using the expanded search range of variables with the initial chromosome size. The points on the line represent the final Pareto frontier for all designs having a DTOC of $135M. The exhaustive search found 2.2 million feasible designs of which 6510 have DTOC of $135M. Only 13 of these designs are non-dominated. The final focused search found 19 non-dominated designs. The focused search was able to push the frontier out further because it used a higher resolution in the design parameter space. This closer spacing of design parameters allowed more design combinations, which yielded some designs that have better performance than those found by the exhaustive search.

Any of the designs found to be non-dominated should be very close to the true Pareto frontier. The final design choice is made with confidence that there is no design with better effectiveness that does not cost more, or a design with equal effectiveness that costs less. No matter what decision process is used, the final selection of the design should be based on the non-dominated frontier.

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7
Conclusion

This thesis proposed use of evolutionary programs to generate non-dominated Pareto frontiers for complicated multi-objective design problems. The method was demonstrated to work on an application to Large Scale Vehicle II.

A need exists for a tool capable of searching a large number of potential designs in concept development. Both New Attack Submarine (NSSN) and next generation aircraft carrier (CVX) evaluated only a very small fraction of the potential concept designs. A great deal of faith was placed in the ship designers to optimize the design, but only a small number of designs were evaluated in formal studies. The evolutionary program developed in this thesis can be applied in a relatively straight forward manner to full scale ship and submarine development. The framework developed in Chapter 3 is very general in nature, and can be applied to any multi-objective design problem. Only the objective attributes and design parameters need be changed.

The evolutionary program is very robust in its search for the Pareto frontier. It is designed to conduct a search that both explores and exploits the design space at the same time. The search method is simple and straight forward to implement. There are many variables that affect the performance of the genetic algorithm, but as long as the variables selected are reasonable, the evolutionary program does well in finding the Pareto frontier. Experimentation to optimize the search program can improve its performance, but any form of the algorithm performs reasonably well.

A new method, multi-attribute iso-effectiveness (MAIE), was proposed to generate combined measures of effectiveness (CMOE) using expert opinion. Unfortunately, not enough data was collected to make a preliminary judgment on the accuracy of this method. The method has a major drawback in that it is very question intensive and requires a significant amount of time from the expert to complete. Because of this, it can only be used to combine 3 or 4 attributes at most. Perhaps this method could be used on a small scale problem to compare responses received from experts using one of the other methods to construct CMOEs discussed in Chapter 3.

If any expert opinion method is used to create an CMOE, extreme care must be used in selecting the parameters (MOEs or MOPs) to combine and the goals and thresholds associated with these parameters. If this initial step is performed improperly, then the rest of the decision analysis is useless. In this thesis, a CMOE was created for hydrodynamic and flexibility. The goals and thresholds selected were based on expert opinion, but it may have been better to re-select the variables and their ranges after initial evaluations. One of the MOPs (number of Froude scale maximum speed runs) did not enter into the decision process at all because all of the non-dominated designs exceeded the goal. Geo-similitude was used as a MOP because it adds value when the model is used to obtain data on current or proposed full-scale submarines. When this MOP was disregarded, no variants with geo-similitude were found on the Pareto frontier. This indicates that if LSV II is being built to assist in development of near-term submarines, then one with geo-similitude should be built. If, on the other hand, LSV II is being built for long-term research, the geo-similitude of future submarines should be built. This

research suggests that a "short, fat" model may be the best option as a prototype for submarines of the future.

Risk was not directly addressed in this thesis, but it can be integrated into the method in one of three ways. It can be treated as a separate objective attribute. Each concept in the design parameter space can be evaluated for risk based on an scale from high to low and the results for all design parameters summed to give a final risk score. If combining certain design parameters either increases or decreases risk, this can be reflected in the final risk score. Another possible method is to combine risk with the cost objective attribute. High risk design characteristics can be assigned a higher cost to offset the risk. A third possible method is to assign each objective attribute an expected range of values. Predicting cost, performance and effectiveness is not always an exact science, and each of these parameters have some uncertainty associated with them. If this uncertainty can by quantified and carried through the problem, then risk can be represented on the Pareto frontier graph as an ovoid around the expected value of objective attributes.

The evolutionary program has been shown to work in a relatively simple submarine model, and should be applicable to full scale ship and submarine concept design. It provides a structured and efficient method for searching design space to obtain the set of non-dominated designs for presentation to the decision-maker. This allows the decision-maker to select one or more of the non-dominated designs for further design. No matter what search method is used, the Pareto frontier should be the starting place for decision makers. Evolutionary programs provide this capability.

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Appendix A: Expert Opinion Surveys

The final 6 pages of this appendix contain the two surveys proposed to obtain expert opinion on hydrodynamic and flexibility combined measures of effectiveness. The first survey uses the Analytical Hierarchy Process (AHP), and the second survey uses multi-attribute iso-effectiveness (MAIE). The survey refers to the MAIE method as "Multi-Attribute Value Analysis". The name of the method was changed to MAIE after the survey was distributed to avoid confusion with a method proposed by Brown[13].

Survey response was not as good as initially hoped. The results from this thesis are based entirely on the author's responses to the survey. A minimal amount of analysis was performed with the data available. The graph on the following page represents this analysis effort.

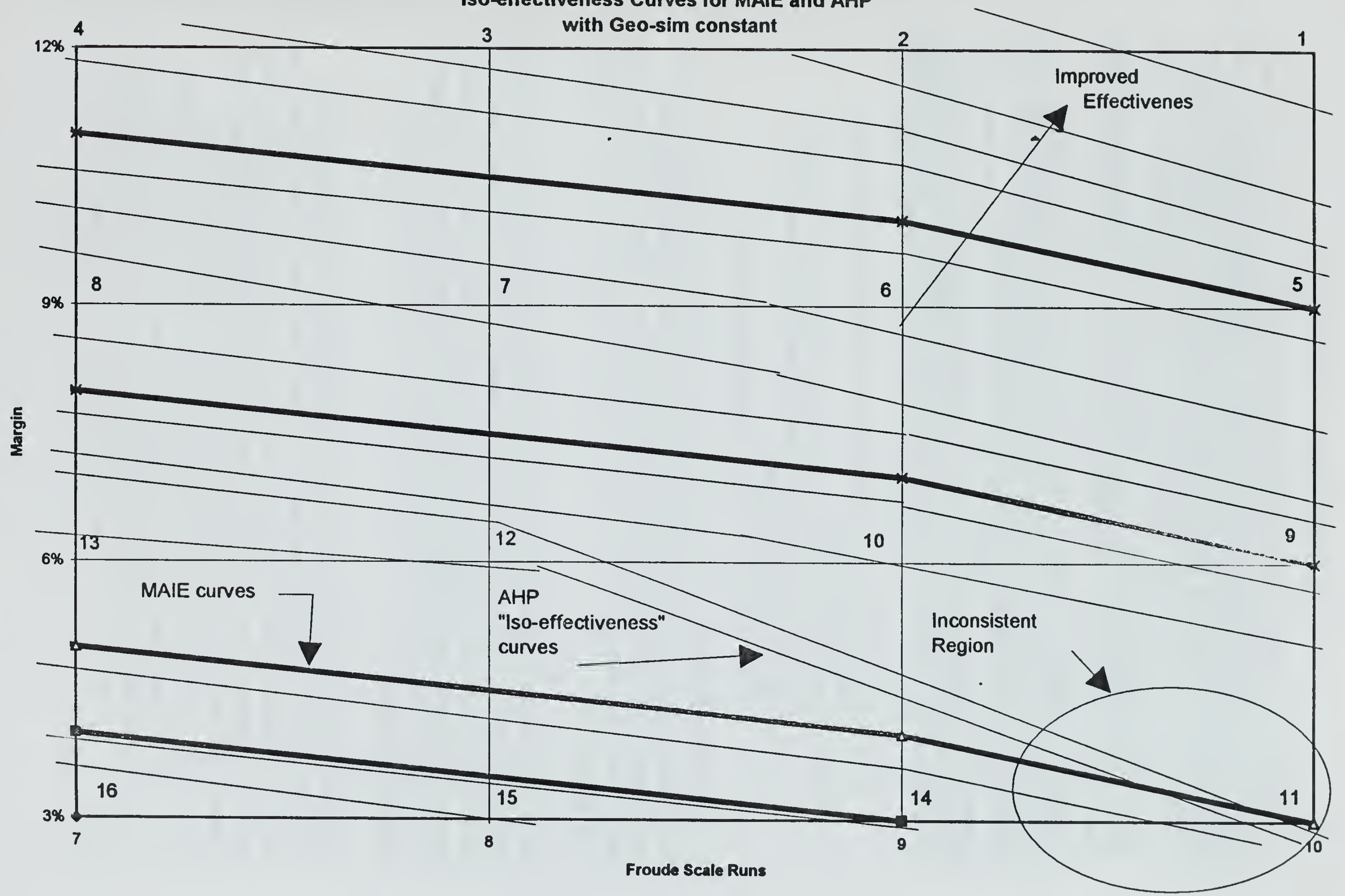
The basis of the graph is the set of iso-effectiveness curves developed from the MAIE method. The bold lines represent the MAIE method iso-effectiveness curves. "Iso-effectiveness" curves were developed for the AHP method by ranking the points evaluated in the AHP survey. The numbers in the field of the plot are the rankings of that point. For example, by the AHP survey, the ranking of number of Froude scale maximum speed runs (FSRs) equal to 8 and margin equal to 9% is 7 out of 16. There are 16 points on this graph evaluated by AHP. The "AHP iso-effectiveness" lines are drawn as the light curves and only represent possible iso-effectiveness curves. They are drawn so that between any two curves there is only one of the points evaluated in the AHP method. There are not two points between two curves, because then another iso-

effectiveness curve could be drawn between them that represents the effectiveness of a value in-between the two points.

If the two methods were completely consistent, then the AHP curves would never cross the MAIE curves. This is not consistently the case, as can be seen in the lower right hand corner. AHP point 11 is on an MAIE curve, yet points 12 and 13 are above this curve. By AHP Point 11 has better effectiveness and by MAIE, points 12 and 13 have better effectiveness.

For most of the design space of this specific example, both methods are consistent. In this one region, however, the two methods disagree. There is not enough data available to determine the reasons for the discrepancies. Further research is needed in this area to determine which method, if any, reflects the expert's true opinion on the topic.

Iso-effectiveness Curves for MAIE and AHP with Geo-sim constant



<u>LSV Hydrodynamic / Flexibility Survey</u>

In this thesis, the LSV design is structured as a multi-attribute decision problem. Three overall attributes are typically the maximum number which can be considered simultaneously by a decision maker. The 3 attributes chosen for this design are cost, hydrodynamic effectiveness and hydro-acoustic / flexibility effectiveness.

The hydro-acoustic and flexibility attribute involves more than one performance metric. Expert opinion must be used to establish and synthesize the relative value of 3 performance variables: Number of Runs at Froude Scale Speed, Margin and Geo-similitude. Two methods of collecting this expert opinion are being investigated: Multi-Attribute Value Analysis and Analytical Hierarchy Process (AHP).

Both methods require the determination of goals and thresholds for each variable. After discussions with LCDR Greg Thomas, I have chosen the following goals and thresholds:

> Number of Runs at Froude Scale Speed that can be performed on one battery charge.
>   Goal = 10, Threshold = 7
> Amount of margin that is available for future growth, including propulsor installation.
>   Goal = 12%, Threshold = 3% (Variant A1 currently has a value of 6.3%)
> The type of geo-similitude that is chosen.
>   Options: NSSN, SSN-21, None (i.e. has "submarine-like shape")

Goals represent the highest value the decision maker believes to be obtainable with the technology available in the time frame of the project, or the value at which further improvement no longer adds significant improvement to the project. Thresholds are the value of minimum acceptable performance. Below this value, it is not worth continuing with the project.

If a member achieves values above the goal, no additional credit is given. It is treated the same as if it had only achieved the goal. If any value is below the threshold, the LSV is assumed to be not feasible. If you do not agree with the variables chosen here, or the goals or thresholds, I would appreciate any feedback you could provide. Obviously, if this first step of the process is flawed, the remainder of the process will not give meaningful results.

The input required for the Multi-Attribute Value Analysis is obtained by the expert answering a set of questions to generate a set of iso-effectiveness curves. For example, if one of the variables is held constant, how much change is required in each of the two remaining variables to give equal effectiveness? Specifically, if geo-similitude is held constant, what value of margin combined with 9 Froude Scale Runs gives equal effectiveness to 10 Froude Scale Runs and 3% margin? If this question is difficult to answer initially, the expert might try to bracket the answer until equivalence point is reached. For example, 12% margin is probably preferred, but 3.5% is probably not. The attached EXCEL file gives the complete survey along with an automatic plot of iso-effectiveness lines.

The second method uses AHP and requires that the expert to make a set of pair-wise comparisons using a questionnaire. First the relative importance of each of the variables is compared. Specifically, the expert must compare Geo-sim to Margin, Geo-sim to Number of Froude Scale Runs, and Margin to Number of Froude Scale Runs. Each of the specific values under each category are then compared to each other specific value within its category. All comparisons are on a scale from 1 to 9, with 1 indicating the choices are equal and 9 indicating that one option is extremely much more important than the other.

There are no correct or incorrect answers to these questions. The value is in obtaining input from the expert decision makers. From my own experience, filling out these types of surveys can be difficult and confusing. I have attempted to make the process as easy as possible, but any feedback you can provide would be much appreciated. If you have any questions or feedback, I can be reached at email aandrew@mit.edu or phone (617) 253-5317. Thank you very much for your time and input.

Name of survey taker:
email:
Phone:

Goals and Thresholds

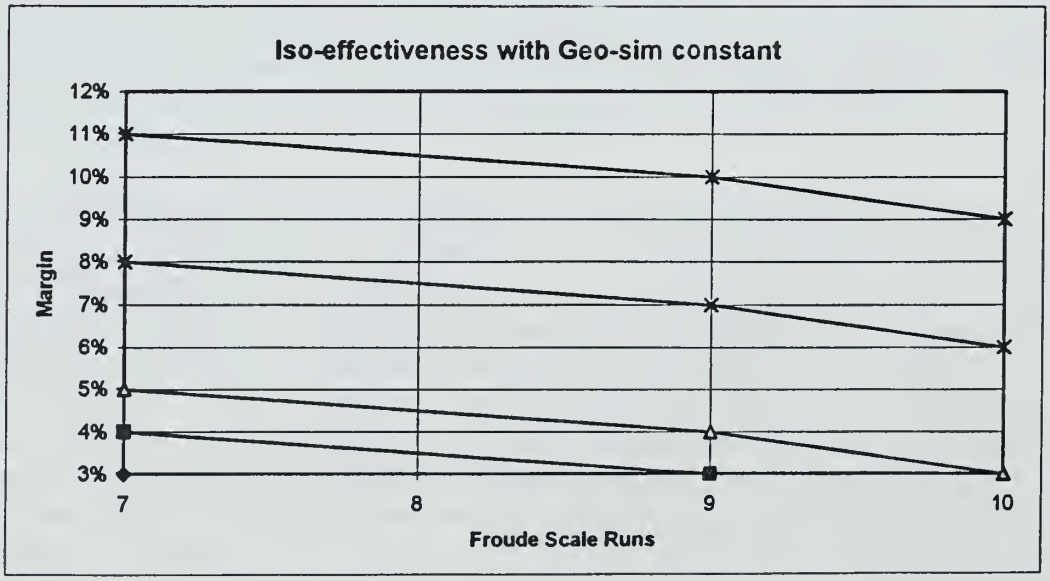
	Threshold	Goal
Froude Run	6	10
Margin	3%	12%

Assuming Geo-similitude is held constant, what value of percent margin (Please enter in colum with number of Froude scale runs (column D) would be required to give equivalence to the number of Froude scale runs (column A) and percent margin (column B)?

Froude Runs	Margin	Froude Runs	Margin
10	3%	9	4%
		7	5%
		6	6%
9	3%	7	4%
		6	5%
7	3%	6	4%
10	6%	9	7%
		7	8%
		6	9%
10	9%	9	10%
		7	11%
		6	12%

Tabulate the data for plotting

	Margin					
Froude Runs	10			3%	6%	9%
	9		3%	4%	7%	10%
	7	3%	4%	5%	8%	11%
	6	4%	5%	6%	9%	12%

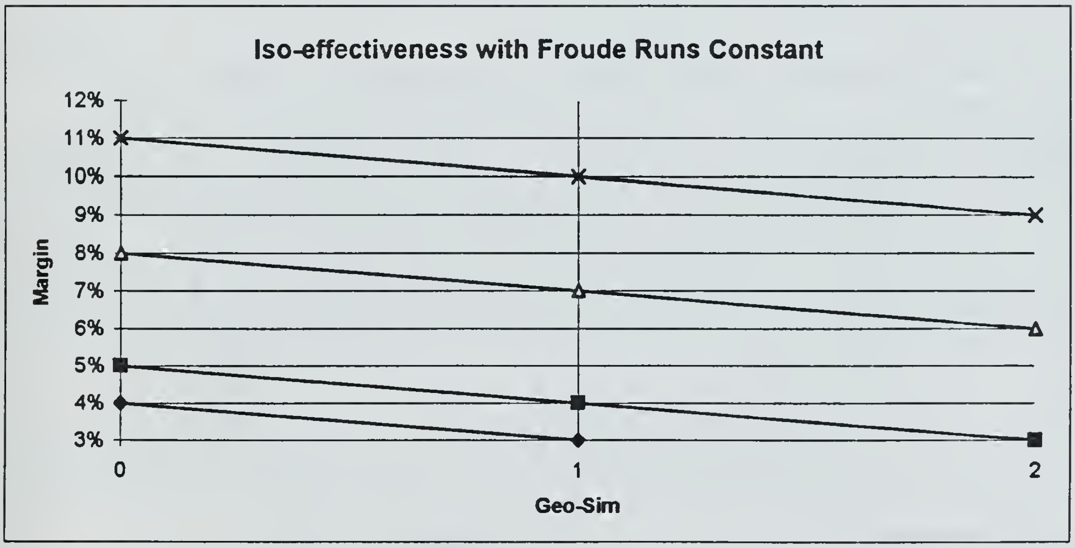


Assuming Number of Froude Scale Runs is held constant, what value of percent margin (Please enter in column E) with given geo-sim (column D) would be required to give equivalence to the geo-sim (column A) and percent margin (column B)?

Geo-sim	Margin	Geo-sim	Margin
NSSN	3%	SSN-21	4%
		None	5%
SSN-21	3%	None	4%
NSSN	6%	SSN-21	7%
		None	8%
NSSN	9%	SSN-21	10%
		None	11%

Tabulate the data for plotting

Geo-sim		Margin			
None	0	4%	5%	8%	11%
SSN-21	1	3%	4%	7%	10%
NSSN	2		3%	6%	9%



LSV Hydrodynamic and Flexibility Effectiveness

Node: 0

Compare the relative IMPORTANCE with respect to: GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	Geo-sim	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Margin
2	Geo-sim	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Fr Runs
3	Margin	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Fr Runs

Abbreviation	Definition
Goal	LSV Hydrodynamic and Flexibility Effectiveness
Geo-sim	Geo-sim of NSSN, SSN-21 or None (i.e. submarine like)
Margin	Percent margin available for furture growth (including propulsor)
Fr Runs	Number of runs that can be performed at Froude scale speed

Node: 30000

Compare the relative PREFERENCE with respect to: Fr Runs < GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	7 Runs	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	8 Runs
2	7 Runs	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	9 Runs
3	7 Runs	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	10 Runs
4	8 Runs	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	9 Runs
5	8 Runs	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	10 Runs
6	9 Runs	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	10 Runs

Abbreviation	Definition
Goal	LSV Hydrodynamic and Flexibility Effectiveness
Fr Runs	Number of runs that can be performed at Froude scale speed
7 Runs	at Froude scale speed
8 Runs	at Froude scale speed
9 Runs	at Froude scale speed
10 Runs	at Froude scale speed

Node: 20000

Compare the relative PREFERENCE with respect to: Margin < GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	3%	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	6%
2	3%	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	9%
3	3%	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	12%
4	6%	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	9%
5	6%	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	12%
6	9%	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	12%

Abbreviation	Definition
Goal	LSV Hydrodynamic and Flexibility Effectiveness
Margin	Percent margin available for furture growth (including propulsor)
3%	margin
6%	margin
9%	margin
12%	margin

Node: 10000

Compare the relative PREFERENCE with respect to: Geo-sim < GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	NSSN	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	SSN-21
2	NSSN	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	None
3	SSN-21	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	None

Abbreviation	Definition
Goal	LSV Hydrodynamic and Flexibility Effectiveness
Geo-sim	Geo-sim of NSSN, SSN-21 or None (i.e. submarine like)
NSSN	Geo-sim is that of New Attack
SSN-21	Geo-sim is that of USS Seawolf
None	Geo-sim is that of a "submarine-like" hull

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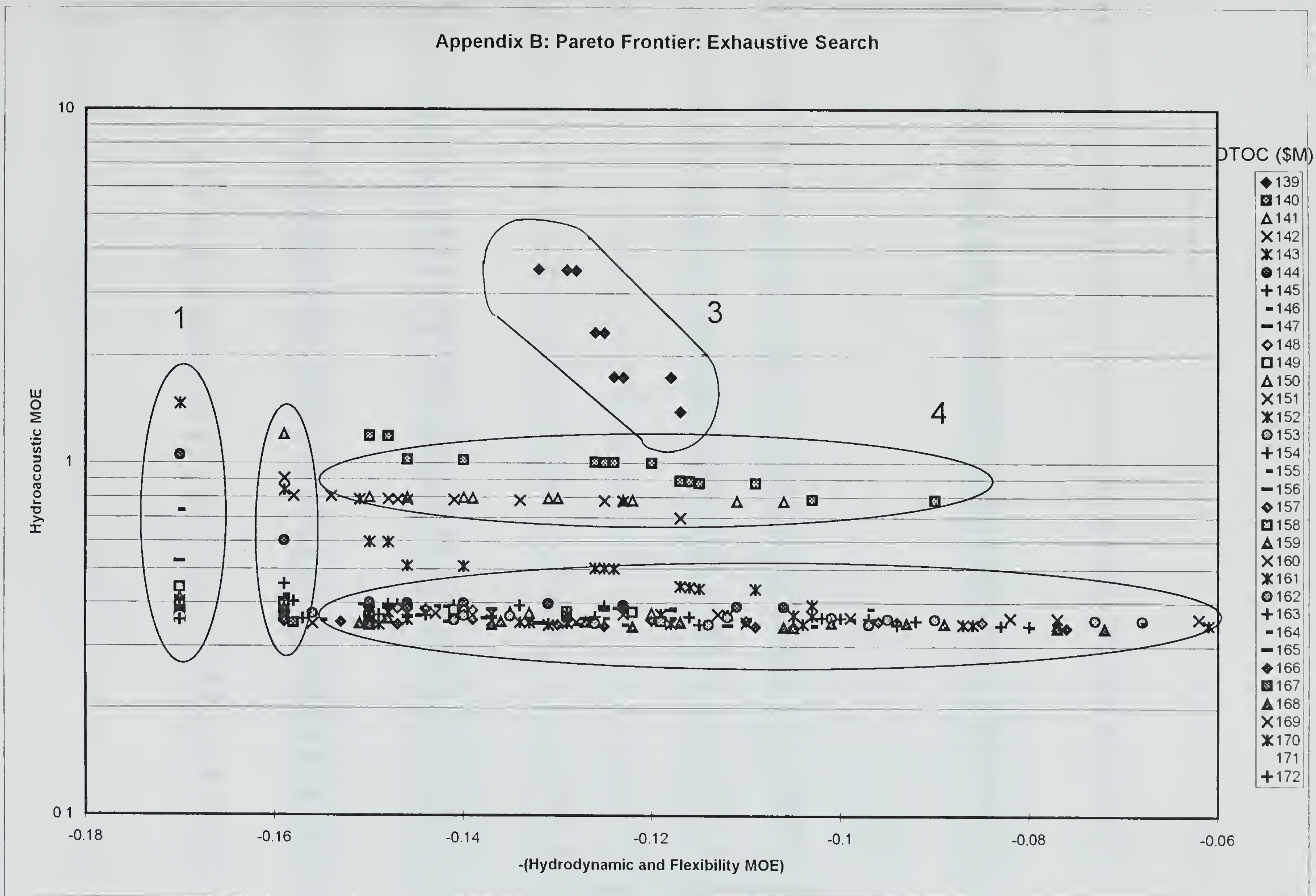

Appendix B: Pareto Frontier: Exhaustive Search
Hydroacoustic MOE
10
1
0 1
-0.18
-0.16
-0.14
-0.12
-0.1
-0.08
-0.06
-(Hydrodynamic and Flexibility MOE)
1
3
4
DTOC ($M)
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
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171
172

Exhaustive Search Design Data Table

Design Nbr.	DTOC ($M)	HAMOE	HD/Flex MOE	D (ft)	L/D	Nf	Na	Batt Type	Batt Pwr (kW)	Coating (in)	Sonar
1	139	1.399	-0.117	14	6	3.68	3.68	1	3000	1.5	1
2	139	1.744	-0.118	14	6	3.36	3.68	1	3000	1.0	1
3	139	1.747	-0.123	14	6	3.36	4.00	1	3000	1.0	1
4	139	1.750	-0.124	14	6	3.68	4.00	1	3000	1.0	1
5	139	2.327	-0.125	14	6	3.36	4.00	1	3000	0.5	1
6	139	2.330	-0.126	14	6	3.68	4.00	1	3000	0.5	1
7	139	3.486	-0.128	14	6	3.36	4.00	1	3000	0.0	1
8	139	3.496	-0.129	14	6	4.00	4.00	1	3000	0.0	1
9	139	3.520	-0.132	15	6	1.75	2.71	1	3000	0.0	1
10	140	0.787	-0.090	15	6	3.36	1.75	1	3000	3.5	1
11	140	0.789	-0.103	15	6	2.71	2.07	1	3000	3.5	1
12	140	0.877	-0.109	13	7	4.00	3.04	1	3000	3.0	1
13	140	0.878	-0.115	13	7	3.68	3.36	1	3000	3.0	1
14	140	0.889	-0.116	15	6	2.39	2.39	1	3000	3.0	1
15	140	0.891	-0.117	15	6	2.71	2.39	1	3000	3.0	1
16	140	1.001	-0.120	13	7	3.04	3.68	1	3000	2.5	1
17	140	1.003	-0.124	13	7	3.04	4.00	1	3000	2.5	1
18	140	1.004	-0.125	13	7	3.36	4.00	1	3000	2.5	1
19	140	1.006	-0.126	13	7	3.68	4.00	1	3000	2.5	1
20	140	1.018	-0.140	15	6	1.75	3.36	1	3000	2.5	1
21	140	1.020	-0.146	15	6	1.75	3.68	1	3000	2.5	1
22	140	1.189	-0.148	15	6	1.75	3.68	1	3000	2.0	1
23	140	1.192	-0.150	15	6	1.75	4.00	1	3000	2.0	1
24	141	0.779	-0.106	12	8	3.68	3.68	1	3000	3.5	1
25	141	0.780	-0.111	12	8	3.68	4.00	1	3000	3.5	1
26	141	0.783	-0.122	13	7	3.36	4.00	1	3000	3.5	1
27	141	0.784	-0.123	13	7	3.68	4.00	1	3000	3.5	1
28	141	0.793	-0.130	14	7	1.75	2.39	1	3000	3.5	1
29	141	0.794	-0.131	15	6	2.07	3.04	1	3000	3.5	1
30	141	0.796	-0.139	14	7	1.75	2.71	1	3000	3.5	1
31	141	0.797	-0.140	15	6	2.07	3.36	1	3000	3.5	1
32	141	0.799	-0.146	15	6	2.07	3.68	1	3000	3.5	1
33	141	0.801	-0.150	15	6	2.07	4.00	1	3000	3.5	1
34	141	1.204	-0.159	14	7	2.71	3.04	1	3000	2.0	1
35	142	0.699	-0.117	14	6	3.68	3.68	1	3000	1.5	2
36	142	0.780	-0.123	14	7	2.07	2.39	1	3233	3.5	1
37	142	0.782	-0.125	14	7	2.39	2.39	1	3233	3.5	1
38	142	0.783	-0.134	15	6	2.39	3.36	1	3233	3.5	1
39	142	0.785	-0.141	15	6	2.39	3.68	1	3233	3.5	1
40	142	0.787	-0.146	15	6	2.39	4.00	1	3233	3.5	1
41	142	0.789	-0.147	15	6	2.71	4.00	1	3233	3.5	1
42	142	0 792	-0.148	15	6	3.36	4.00	1	3233	3.5	1

Design Nbr.	DTOC ($M)	HAMOE	HD/Flex MOE	D (ft)	L/D	Nf	Na	Batt Type	Batt Pwr (kW)	Coating (in)	Sonar
43	142	0.805	-0.154	13	8	2.71	3.04	1	3000	3.5	1
44	142	0.806	-0.158	14	7	2.71	3.04	1	3000	3.5	1
45	142	0.905	-0.159	14	7	2.71	3.04	1	3000	3.0	1
46	143	0.394	-0.103	15	6	2.71	2.07	1	3000	3.5	2
47	143	0.438	-0.109	13	7	4.00	3.04	1	3000	3.0	2
48	143	0.439	-0.115	13	7	3.68	3.36	1	3000	3.0	2
49	143	0.444	-0.116	15	6	2.39	2.39	1	3000	3.0	2
50	143	0.446	-0.117	15	6	2.71	2.39	1	3000	3.0	2
51	143	0.501	-0.124	13	7	3.04	4.00	1	3000	2.5	2
52	143	0.502	-0.125	13	7	3.36	4.00	1	3000	2.5	2
53	143	0.503	-0.126	13	7	3.68	4.00	1	3000	2.5	2
54	143	0.509	-0.140	15	6	1.75	3.36	1	3000	2.5	2
55	143	0.510	-0.146	15	6	1.75	3.68	1	3000	2.5	2
56	143	0.595	-0.148	15	6	1.75	3.68	1	3000	2.0	2
57	143	0.596	-0.150	15	6	1.75	4.00	1	3000	2.0	2
58	143	0.789	-0.151	14	7	2.71	3.04	1	3233	3.5	1
59	143	0.839	-0.159	15	7	2.71	3.04	1	3000	3.5	1
60	143	1.467	-0.170	12	10	2.39	2.71	1	3000	1.5	1
61	144	0.389	-0.106	12	8	3.68	3.68	1	3000	3.5	2
62	144	0.390	-0.111	12	8	3.68	4.00	1	3000	3.5	2
63	144	0.392	-0.123	13	7	3.68	4.00	1	3000	3.5	2
64	144	0.397	-0.131	15	6	2.07	3.04	1	3000	3.5	2
65	144	0.398	-0.140	15	6	2.07	3.36	1	3000	3.5	2
66	144	0.399	-0.146	15	6	2.07	3.68	1	3000	3.5	2
67	144	0.400	-0.150	15	6	2.07	4.00	1	3000	3.5	2
68	144	0.602	-0.159	14	7	2.71	3.04	1	3000	2.0	2
69	144	1.051	-0.170	12	10	2.39	2.71	1	3000	2.5	1
70	145	0.390	-0.123	14	7	2.07	2.39	1	3233	3.5	2
71	145	0.391	-0.125	14	7	2.39	2.39	1	3233	3.5	2
72	145	0.392	-0.134	15	6	2.39	3.36	1	3233	3.5	2
73	145	0.393	-0.141	15	6	2.39	3.68	1	3233	3.5	2
74	145	0.394	-0.146	15	6	2.39	4.00	1	3233	3.5	2
75	145	0.395	-0.147	15	6	2.71	4.00	1	3233	3.5	2
76	145	0.395	-0.147	15	6	3.04	4.00	1	3233	3.5	2
77	145	0.396	-0.148	15	6	3.36	4.00	1	3233	3.5	2
78	145	0.403	-0.158	14	7	2.71	3.04	1	3000	3.5	2
79	145	0.453	-0.159	14	7	2.71	3.04	1	3000	3.0	2
80	146	0.383	-0.097	14	7	3.36	1.75	1	3467	3.5	2
81	146	0.384	-0.118	14	7	2.39	2.39	1	3467	3.5	2
82	146	0.386	-0.124	15	6	3.36	3.04	1	3467	3.5	2
83	146	0.387	-0.140	15	6	2.71	4.00	1	3467	3.5	2
84	146	0.388	-0.141	15	6	3.04	4.00	1	3467	3.5	2
85	146	0.389	-0.142	15	6	3.36	4.00	1	3467	3.5	2
86	146	0.390	-0.143	15	6	3.68	4.00	1	3467	3.5	2

Design Nbr.	DTOC ($M)	HAMOE	HD/Flex MOE	D (ft)	L/D	Nf	Na	Batt Type	Batt Pwr (kW)	Coating (in)	Sonar
87	146	0.392	-0.146	14	7	1.75	3.36	1	3233	3.5	2
88	146	0.393	-0.150	14	7	1.75	3.68	1	3233	3.5	2
89	146	0.395	-0.151	14	7	2.71	3.04	1	3233	3.5	2
90	146	0.420	-0.159	15	7	2.71	3.04	1	3000	3.5	2
91	146	0.734	-0.170	12	10	2.39	2.71	1	3000	1.5	2
92	147	0.381	-0.118	15	6	4.00	3.04	1	3700	3.5	2
93	147	0.382	-0.125	15	6	4.00	3.36	1	3700	3.5	2
94	147	0.382	-0.125	15	6	3.68	3.36	1	3700	3.5	2
95	147	0.383	-0.137	15	6	3.68	4.00	1	3700	3.5	2
96	147	0.386	-0.144	14	7	1.75	3.68	1	3467	3.5	2
97	147	0.387	-0.148	14	7	1.75	4.00	1	3467	3.5	2
98	147	0.388	-0.150	14	7	2.07	4.00	1	3467	3.5	2
99	147	0.410	-0.159	15	7	2.71	3.04	1	3233	3.5	2
100	147	0.526	-0.170	12	10	2.71	2.71	1	3000	2.5	2
101	147	0.526	-0.170	12	10	2.39	2.71	1	3000	2.5	2
102	148	0.381	-0.139	14	7	2.71	3.04	1	3700	3.5	2
103	148	0.382	-0.140	14	7	2.39	3.68	1	3700	3.5	2
104	148	0.383	-0.144	14	7	2.39	4.00	1	3700	3.5	2
105	148	0.384	-0.146	14	7	3.04	4.00	1	3700	3.5	2
106	148	0.385	-0.147	14	7	3.68	4.00	1	3700	3.5	2
107	148	0.401	-0.159	15	7	2.71	3.04	1	3467	3.5	2
108	149	0.376	-0.122	13	8	2.71	3.36	1	3933	3.5	2
109	149	0.377	-0.129	13	8	2.39	4.00	1	3933	3.5	2
110	149	0.381	-0.141	14	7	4.00	4.00	1	3933	3.5	2
111	149	0.394	-0.159	15	7	2.71	3.04	1	3700	3.5	2
112	149	0.442	-0.170	12	11	2.71	2.71	1	3000	3.5	2
113	149	0.442	-0.170	12	11	2.39	2.71	1	3000	3.5	2
114	149	0.442	-0.170	13	10	2.71	2.71	1	3000	3.5	2
115	149	0.442	-0.170	13	10	2.39	2.71	1	3000	3.5	2
116	150	0.373	-0.120	13	8	3.36	3.68	1	4167	3.5	2
117	150	0.374	-0.133	14	7	3.36	4.00	1	4167	3.5	2
118	150	0.375	-0.135	14	7	4.00	4.00	1	4167	3.5	2
119	150	0.384	-0.150	15	7	1.75	2.71	1	3933	3.5	2
120	150	0.388	-0.159	15	7	2.71	3.04	1	3933	3.5	2
121	150	0.413	-0.170	12	11	2.71	2.71	1	3233	3.5	2
122	150	0.413	-0.170	12	11	2.39	2.71	1	3233	3.5	2
123	151	0.359	-0.062	10	8	3.04	3.04	4	3000	3.5	2
124	151	0.360	-0.077	10	8	2.71	4.00	4	3000	3.5	2
125	151	0.360	-0.077	10	8	2.39	4.00	4	3000	3.5	2
126	151	0.362	-0.082	11	7	3.04	3.04	4	3000	3.5	2
127	151	0.363	-0.099	11	7	2.39	4.00	4	3000	3.5	2
128	151	0.370	-0.113	13	6	1.75	2.71	4	3000	3.5	2
129	151	0.371	-0.123	13	6	1.75	3.04	4	3000	3.5	2
130	151	0.372	-0.137	13	6	1.75	3.68	4	3000	3.5	2

Design Nbr.	DTOC ($M)	HAMOE	HD/Flex MOE	D (ft)	L/D	Nf	Na	Batt Type	Batt Pwr (kW)	Coating (in)	Sonar
131	151	0.373	-0.143	13	6	1.75	4.00	4	3000	3.5	2
132	151	0.381	-0.150	15	7	2.71	2.71	1	4167	3.5	2
133	151	0.381	-0.150	15	7	1.75	3.04	1	4167	3.5	2
134	151	0.381	-0.150	15	7	2.07	3.04	1	4167	3.5	2
135	151	0.381	-0.150	15	7	1.75	3.36	1	4167	3.5	2
136	151	0.381	-0.150	15	7	1.75	3.68	1	4167	3.5	2
137	151	0.382	-0.159	15	7	2.71	3.04	1	4167	3.5	2
138	151	0.404	-0.170	12	11	2.39	2.71	1	3467	3.5	2
139	152	0.367	-0.103	10	9	1.75	4.00	4	3000	3.5	2
140	152	0.368	-0.105	11	8	1.75	2.39	4	3000	3.5	2
141	152	0.369	-0.112	11	8	1.75	2.71	4	3000	3.5	2
142	152	0.370	-0.119	11	8	1.75	3.04	4	3000	3.5	2
143	152	0.371	-0.129	11	8	1.75	3.68	4	3000	3.5	2
144	152	0.374	-0.146	12	7	1.75	4.00	4	3000	3.5	2
145	152	0.375	-0.148	15	7	1.75	3.04	1	4400	3.5	2
146	152	0.376	-0.150	15	7	1.75	3.36	1	4400	3.5	2
147	152	0.376	-0.150	15	7	1.75	3.68	1	4400	3.5	2
148	152	0.381	-0.159	15	7	2.71	3.04	1	4400	3.5	2
149	152	0.397	-0.170	12	11	2.71	2.71	1	3700	3.5	2
150	152	0.397	-0.170	12	11	2.39	2.71	1	3700	3.5	2
151	153	0.355	-0.068	10	8	3.04	3.68	4	3233	3.5	2
152	153	0.356	-0.073	10	8	3.36	4.00	4	3233	3.5	2
153	153	0.356	-0.073	10	8	3.04	4.00	4	3233	3.5	2
154	153	0.358	-0.090	11	7	3.04	3.68	4	3233	3.5	2
155	153	0.359	-0.095	11	7	3.36	4.00	4	3233	3.5	2
156	153	0.359	-0.095	11	7	3.04	4.00	4	3233	3.5	2
157	153	0.363	-0.101	12	7	1.75	2.07	4	3233	3.5	2
158	153	0.364	-0.112	12	7	1.75	2.39	4	3233	3.5	2
159	153	0.366	-0.135	13	6	1.75	3.68	4	3233	3.5	2
160	153	0.367	-0.140	13	6	1.75	4.00	4	3233	3.5	2
161	153	0.372	-0.150	15	7	2.07	3.36	1	4633	3.5	2
162	153	0.372	-0.150	15	7	1.75	3.68	1	4633	3.5	2
163	153	0.373	-0.156	15	7	2.71	3.04	1	4633	3.5	2
164	153	0.396	-0.170	13	10	2.39	2.71	1	3933	3.5	2
165	154	0.355	-0.092	11	7	3.36	4.00	4	3467	3.5	2
166	154	0.361	-0.097	10	9	1.75	3.68	4	3233	3.5	2
167	154	0.362	-0.100	10	9	1.75	4.00	4	3233	3.5	2
168	154	0.362	-0.100	10	9	2.07	4.00	4	3233	3.5	2
169	154	0.363	-0.102	11	8	1.75	2.39	4	3233	3.5	2
170	154	0.364	-0.116	11	8	1.75	3.04	4	3233	3.5	2
171	154	0.365	-0.126	11	8	1.75	3.68	4	3233	3.5	2
172	154	0.368	-0.144	12	7	1.75	4.00	4	3233	3.5	2
173	154	0.369	-0.149	15	7	2.71	3.04	1	4867	3.5	2
174	154	0.369	-0.149	15	7	2.07	3.68	1	4867	3.5	2

Design Nbr.	DTOC ($M)	HAMOE	HD/Flex MOE	D (ft)	L/D	Nf	Na	Batt Type	Batt Pwr (kW)	Coating (in)	Sonar
175	154	0.370	-0.150	15	7	2.39	3.68	1	4867	3.5	2
176	154	0.370	-0.150	15	7	2.07	4.00	1	4867	3.5	2
177	154	0.390	-0.170	13	10	2.39	2.71	1	4167	3.5	2
178	155	0.352	-0.068	10	8	4.00	4.00	4	3467	3.5	2
179	155	0.358	-0.099	11	8	1.75	2.39	4	3467	3.5	2
180	155	0.359	-0.110	12	7	1.75	2.39	4	3467	3.5	2
181	155	0.360	-0.118	12	7	1.75	2.71	4	3467	3.5	2
182	155	0.361	-0.125	12	7	1.75	3.04	4	3467	3.5	2
183	155	0.362	-0.138	12	7	1.75	3.68	4	3467	3.5	2
184	155	0.367	-0.145	15	7	2.71	3.04	1	5100	3.5	2
185	155	0.368	-0.150	15	7	2.39	4.00	1	5100	3.5	2
186	155	0.378	-0.159	12	9	2.71	3.04	3	3700	3.5	2
187	155	0.385	-0.170	13	10	2.39	2.71	1	4400	3.5	2
188	155	0.385	-0.170	13	10	2.71	2.71	1	4400	3.5	2
189	156	0.357	-0.096	10	9	1.75	4.00	4	3467	3.5	2
190	156	0.360	-0.119	11	8	1.75	3.36	4	3467	3.5	2
191	156	0.361	-0.127	11	8	1.75	4.00	4	3467	3.5	2
192	156	0.363	-0.141	12	7	1.75	4.00	4	3467	3.5	2
193	156	0.376	-0.159	13	8	2.71	3.04	3	3933	3.5	2
194	156	0.381	-0.170	13	10	2.39	2.71	1	4633	3.5	2
195	156	0.381	-0.170	13	10	2.71	2.71	1	4633	3.5	2
196	157	0.352	-0.085	10	9	1.75	3.36	4	3700	3.5	2
197	157	0.353	-0.094	10	9	2.07	4.00	4	3700	3.5	2
198	157	0.354	-0.096	11	8	1.75	2.39	4	3700	3.5	2
199	157	0.355	-0.110	11	8	1.75	3.04	4	3700	3.5	2
200	157	0.356	-0.120	11	8	1.75	3.68	4	3700	3.5	2
201	157	0.357	-0.129	12	7	1.75	3.36	4	3700	3.5	2
202	157	0.358	-0.139	12	7	1.75	4.00	4	3700	3.5	2
203	157	0.374	-0.159	12	8	2.71	3.04	4	3467	3.5	2
204	158	0.354	-0.119	13	6	2.39	3.36	4	3933	3.5	2
205	158	0.365	-0.150	14	6	1.75	3.04	4	3700	3.5	2
206	159	0.348	-0.077	10	9	1.75	3.04	4	3933	3.5	2
207	159	0.349	-0.089	10	9	1.75	4.00	4	3933	3.5	2
208	159	0.350	-0.093	11	8	1.75	2.39	4	3933	3.5	2
209	159	0.351	-0.101	11	8	1.75	2.71	4	3933	3.5	2
210	159	0.352	-0.117	11	8	1.75	3.68	4	3933	3.5	2
211	159	0.353	-0.127	12	7	1.75	3.36	4	3933	3.5	2
212	159	0.354	-0.136	12	7	1.75	4.00	4	3933	3.5	2
213	159	0.361	-0.148	14	6	1.75	3.04	4	3933	3.5	2
214	159	0.362	-0.150	14	6	1.75	3.36	4	3933	3.5	2
215	159	0.369	-0.159	12	8	2.71	3.04	4	3700	3.5	2
216	159	0.376	-0.170	12	10	2.39	2.71	3	4167	3.5	2
217	160	0.351	-0.110	13	6	3.04	3.04	4	4167	3.5	2
218	160	0.352	-0.128	13	6	2.39	4.00	4	4167	3.5	2

Design Nbr.	DTOC ($M)	HAMOE	HD/Flex MOE	D (ft)	L/D	Nf	Na	Batt Type	Batt Pwr (kW)	Coating (in)	Sonar
219	160	0.365	-0.159	13	7	2.71	3.04	4	3933	3.5	2
220	160	0.372	-0.170	12	10	2.71	2.71	3	4400	3.5	2
221	160	0.372	-0.170	12	10	2.39	2.71	3	4400	3.5	2
222	161	0.345	-0.061	10	9	2.71	2.39	4	4167	3.5	2
223	161	0.346	-0.086	10	9	1.75	4.00	4	4167	3.5	2
224	161	0.347	-0.087	10	9	2.07	4.00	4	4167	3.5	2
225	161	0.348	-0.104	11	8	1.75	3.04	4	4167	3.5	2
226	161	0.349	-0.118	11	8	1.75	4.00	4	4167	3.5	2
227	161	0.350	-0.129	12	7	1.75	3.68	4	4167	3.5	2
228	161	0.351	-0.133	12	7	1.75	4.00	4	4167	3.5	2
229	161	0.352	-0.134	12	7	2.07	4.00	4	4167	3.5	2
230	161	0.356	-0.137	14	6	1.75	2.71	4	4167	3.5	2
231	161	0.357	-0.146	14	6	1.75	3.04	4	4167	3.5	2
232	161	0.358	-0.150	14	6	1.75	3.36	4	4167	3.5	2
233	161	0.358	-0.150	14	6	1.75	3.68	4	4167	3.5	2
234	161	0.364	-0.159	12	8	2.71	3.04	4	3933	3.5	2
235	162	0.346	-0.097	12	7	2.39	2.39	4	4400	3.5	2
236	162	0.347	-0.114	12	7	2.07	3.04	4	4400	3.5	2
237	162	0.349	-0.126	13	6	2.71	4.00	4	4400	3.5	2
238	162	0.356	-0.141	11	9	1.75	3.68	4	4167	3.5	2
239	162	0.361	-0.159	13	7	2.71	3.04	4	4167	3.5	2
240	162	0.368	-0.170	12	10	2.71	2.71	3	4633	3.5	2
241	162	0.368	-0.170	12	10	2.39	2.71	3	4633	3.5	2
242	163	0.343	-0.080	10	9	2.71	3.04	4	4400	3.5	2
243	163	0.344	-0.083	10	9	2.71	4.00	4	4400	3.5	2
244	163	0.344	-0.083	10	9	2.39	4.00	4	4400	3.5	2
245	163	0.344	-0.083	10	9	2.07	4.00	4	4400	3.5	2
246	163	0.345	-0.094	11	8	2.07	2.71	4	4400	3.5	2
247	163	0.346	-0.115	11	8	1.75	4.00	4	4400	3.5	2
248	163	0.348	-0.131	12	7	2.07	4.00	4	4400	3.5	2
249	163	0.354	-0.150	14	6	1.75	3.36	4	4400	3.5	2
250	163	0.360	-0.157	12	8	2.71	3.04	4	4167	3.5	2
251	164	0.341	-0.080	10	9	2.39	4.00	4	4633	3.5	2
252	164	0.343	-0.103	11	8	2.07	3.36	4	4633	3.5	2
253	164	0.345	-0.123	12	7	2.07	3.68	4	4633	3.5	2
254	164	0.346	-0.128	12	7	2.07	4.00	4	4633	3.5	2
255	164	0.353	-0.142	11	9	1.75	4.00	4	4400	3.5	2
256	164	0.356	-0.155	12	8	2.71	3.04	4	4400	3.5	2
257	164	0.357	-0.159	13	7	2.71	3.04	4	4400	3.5	2
258	165	0.344	-0.112	11	8	2.07	4.00	4	4633	3.5	2
259	165	0.350	-0.132	14	6	1.75	2.71	4	4633	3.5	2
260	165	0.351	-0.149	14	6	1.75	3.36	4	4633	3.5	2
261	165	0.352	-0.150	13	7	1.75	3.04	4	4633	3.5	2
262	165	0.352	-0.150	14	6	1.75	3.68	4	4633	3.5	2

Design Nbr.	DTOC ($M)	HAMOE	HD/Flex MOE	D (ft)	L/D	Nf	Na	Batt Type	Batt Pwr (kW)	Coating (in)	Sonar
263	165	0.352	-0.150	14	6	1.75	4.00	4	4633	3.5	2
264	166	0.339	-0.076	10	9	3.04	4.00	4	4867	3.5	2
265	166	0.341	-0.105	11	8	2.71	3.04	4	4867	3.5	2
266	166	0.342	-0.109	11	8	2.07	4.00	4	4867	3.5	2
267	166	0.342	-0.109	11	8	2.71	4.00	4	4867	3.5	2
268	166	0.343	-0.125	12	7	2.39	4.00	4	4867	3.5	2
269	166	0.347	-0.130	14	6	1.75	2.71	4	4867	3.5	2
270	166	0.348	-0.147	14	6	1.75	3.36	4	4867	3.5	2
271	166	0.353	-0.153	12	8	2.71	3.04	4	4633	3.5	2
272	166	0.354	-0.159	13	7	2.71	3.04	4	4633	3.5	2
273	167	0.349	-0.150	13	7	1.75	3.04	4	4867	3.5	2
274	167	0.349	-0.150	14	6	1.75	3.68	4	4867	3.5	2
275	167	0.349	-0.150	14	6	1.75	4.00	4	4867	3.5	2
276	167	0.351	-0.158	13	7	2.71	3.04	4	4867	3.5	2
277	167	0.366	-0.170	11	11	2.39	2.71	4	4400	3.5	2
278	168	0.338	-0.072	10	9	4.00	4.00	4	5100	3.5	2
279	168	0.338	-0.072	10	9	3.68	4.00	4	5100	3.5	2
280	168	0.339	-0.077	11	8	3.68	2.39	4	5100	3.5	2
281	168	0.340	-0.105	11	8	2.39	4.00	4	5100	3.5	2
282	168	0.341	-0.106	11	8	3.04	4.00	4	5100	3.5	2
283	168	0.341	-0.106	11	8	3.36	4.00	4	5100	3.5	2
284	168	0.341	-0.106	11	8	2.71	4.00	4	5100	3.5	2
285	168	0.342	-0.122	12	7	2.71	4.00	4	5100	3.5	2
286	168	0.346	-0.137	14	6	1.75	3.04	4	5100	3.5	2
287	168	0.347	-0.150	14	6	1.75	3.68	4	5100	3.5	2
288	168	0.350	-0.151	12	8	2.71	3.04	4	4867	3.5	2
289	169	0.345	-0.131	11	9	1.75	3.68	4	5100	3.5	2
290	169	0.349	-0.156	13	7	2.71	3.04	4	5100	3.5	2
291	169	0.363	-0.170	11	11	2.71	2.71	4	4633	3.5	2
292	169	0.363	-0.170	11	11	2.39	2.71	4	4633	3.5	2
293	170	0.347	-0.149	14	6	1.75	3.68	4	5333	3.5	2
294	171	0.359	-0.170	11	11	2.39	2.71	4	4867	3.5	2
295	172	0.357	-0.170	11	11	2.39	2.71	4	5100	3.5	2

Design Nbr.	Disp (lton)	Margin (ltons)	Margin/Disp	FSR's	HSR's	Max Speed	Geo Sim	Acqu Cost ($M)	Scale
1	248	21.6	0.087	20	3	32.4	0	47.4	0.29
2	243	21.5	0.088	20	3	32.5	0	47.2	0.29
3	247	23.0	0.093	20	3	32.4	0	47.3	0.29
4	250	23.6	0.094	20	3	32.4	0	47.3	0.29
5	245	23.2	0.095	20	3	32.5	0	47.2	0.29
6	248	23.8	0.096	20	3	32.4	0	47.2	0.29
7	243	23.7	0.098	21	3	32.5	0	47.0	0.29
8	249	24.6	0.099	20	3	32.4	0	47.1	0.29
9	246	25.0	0.102	20	3	32.1	0	47.4	0.29
10	256	15.4	0.060	18	3	31.9	0	48.3	0.30
11	260	19.1	0.073	18	3	31.8	0	48.4	0.30
12	248	19.5	0.079	19	3	32.3	0	48.4	0.29
13	251	21.3	0.085	19	3	32.2	0	48.4	0.29
14	263	22.6	0.086	18	3	31.7	0	48.3	0.30
15	269	23.5	0.087	17	3	31.6	0	48.4	0.30
16	247	22.3	0.090	19	3	32.3	0	48.3	0.29
17	250	23.6	0.094	19	3	32.2	0	48.3	0.29
18	253	24.0	0.095	19	3	32.2	0	48.4	0.29
19	256	24.4	0.096	19	3	32.1	0	48.4	0.30
20	271	29.8	0.110	18	3	31.7	0	48.3	0.30
21	277	32.2	0.116	17	3	31.6	0	48.4	0.30
22	274	32.3	0.118	18	3	31.6	0	48.3	0.30
23	280	34.7	0.124	17	3	31.5	0	48.3	0.30
24	243	18.4	0.076	19	3	32.3	0	49.0	0.29
25	245	19.8	0.081	19	3	32.2	0	49.0	0.29
26	257	23.7	0.092	18	3	32.1	0	48.6	0.30
27	260	24.1	0.093	18	3	32.0	0	48.7	0.30
28	268	26.7	0.100	17	3	31.6	0	49.2	0.30
29	276	28.0	0.101	17	3	31.5	0	48.6	0.30
30	275	29.9	0.109	17	3	31.4	0	49.4	0.30
31	283	31.0	0.110	16	3	31.4	0	48.7	0.31
32	289	33.4	0.116	16	3	31.3	0	48.8	0.31
33	294	35.8	0.122	16	3	31.2	0	48.9	0.31
34	291	35.7	0.123	17	3	31.1	1	49.3	0.31
35	248	21.6	0.087	20	3	32.4	0	47.4	0.29
36	274	25.6	0.093	17	3	32.2	0	49.7	0.30
37	279	26.5	0.095	17	3	32.1	0	49.8	0.30
38	289	30.0	0.104	17	3	32.1	0	49.2	0.31
39	295	32.7	0.111	16	3	32.0	0	49.3	0.31
40	300	34.8	0.116	16	3	31.9	0	49.4	0.31
41	306	35.7	0.117	16	3	31.8	0	49.5	0.31
42	315	37.2	0.118	15	3	31.6	0	49.6	0.32

Design Nbr.	Disp (lton)	Margin (ltons)	Margin/Disp	FSR's	HSR's	Max Speed	Geo Sim	Acqu Cost ($M)	Scale
43	290	33.4	0.115	16	3	31.0	1	50.3	0.31
44	298	35.5	0.119	15	3	31.0	1	49.8	0.31
45	296	35.6	0.121	16	3	31.0	1	49.6	0.31
46	260	19.1	0.073	18	3	31.8	0	48.4	0.30
47	248	19.5	0.079	19	3	32.3	0	48.4	0.29
48	251	21.3	0.085	19	3	32.2	0	48.4	0.29
49	263	22.6	0.086	18	3	31.7	0	48.3	0.30
50	269	23.5	0.087	17	3	31.6	0	48.4	0.30
51	250	23.6	0.094	19	3	32.2	0	48.3	0.29
52	253	24.0	0.095	19	3	32.2	0	48.4	0.29
53	256	24.4	0.096	19	3	32.1	0	48.4	0.30
54	271	29.8	0.110	18	3	31.7	0	48.3	0.30
55	277	32.2	0.116	17	3	31.6	0	48.4	0.30
56	274	32.3	0.118	18	3	31.6	0	48.3	0.30
57	280	34.7	0.124	17	3	31.5	0	48.3	0.30
58	298	33.6	0.113	16	3	31.8	1	50.2	0.31
59	365	55.9	0.153	12	3	29.7	1	51.3	0.33
60	292	36.3	0.124	16	3	30.6	2	51.4	0.31
61	243	18.4	0.076	19	3	32.3	0	49.0	0.29
62	245	19.8	0.081	19	3	32.2	0	49.0	0.29
63	260	24.1	0.093	18	3	32.0	0	48.7	0.30
64	276	28.0	0.101	17	3	31.5	0	48.6	0.30
65	283	31.0	0.110	16	3	31.4	0	48.7	0.31
66	289	33.4	0.116	16	3	31.3	0	48.8	0.31
67	294	35.8	0.122	16	3	31.2	0	48.9	0.31
68	291	35.7	0.123	17	3	31.1	1	49.3	0.31
69	297	36.0	0.121	16	3	30.5	2	51.7	0.31
70	274	25.6	0.093	17	3	32.2	0	49.7	0.30
71	279	26.5	0.095	17	3	32.1	0	49.8	0.30
72	289	30.0	0.104	17	3	32.1	0	49.2	0.31
73	295	32.7	0.111	16	3	32.0	0	49.3	0.31
74	300	34.8	0.116	16	3	31.9	0	49.4	0.31
75	306	35.7	0.117	16	3	31.8	0	49.5	0.31
76	311	36.3	0.117	16	3	31.7	0	49.6	0.31
77	315	37.2	0.118	15	3	31.6	0	49.6	0.32
78	298	35.5	0.119	15	3	31.0	1	49.8	0.31
79	296	35.6	0.121	16	3	31.0	1	49.6	0.31
80	272	18.2	0.067	18	3	33.0	0	50.1	0.30
81	279	24.5	0.088	18	3	32.9	0	50.2	0.30
82	298	27.9	0.094	17	3	32.7	0	49.7	0.31
83	306	33.7	0.110	16	3	32.5	0	49.9	0.31
84	311	34.4	0.111	16	3	32.4	0	49.9	0.31
85	315	35.3	0.112	16	3	32.4	0	50.0	0.32
86	319	36.0	0.113	16	3	32.3	0	50.1	0.32

Design Nbr.	Disp (lton)	Margin (ltons)	Margin/Disp	FSR's	HSR's	Max Speed	Geo Sim	Acqu Cost ($M)	Scale
87	287	33.2	0.116	17	3	32.0	0	49.9	0.31
88	292	35.4	0.121	16	3	31.9	0	50.0	0.31
89	298	33.6	0.113	16	3	31.8	1	50.2	0.31
90	365	55.9	0.153	12	3	29.7	1	51.3	0.33
91	292	36.3	0.124	16	3	30.6	2	51.4	0.31
92	305	27.0	0.088	17	3	33.2	0	50.2	0.31
93	312	29.7	0.095	17	3	33.1	0	50.3	0.32
94	308	29.4	0.095	17	3	33.2	0	50.3	0.31
95	319	34.1	0.107	16	3	33.0	0	50.4	0.32
96	292	33.2	0.114	17	3	32.7	0	50.4	0.31
97	296	35.0	0.118	17	3	32.6	0	50.5	0.31
98	303	36.6	0.121	17	3	32.5	0	50.6	0.31
99	365	54.2	0.148	13	3	30.4	1	51.7	0.33
100	300	36.3	0.121	15	3	30.4	2	51.8	0.31
101	297	36.0	0.121	16	3	30.5	2	51.7	0.31
102	298	29.6	0.099	17	3	33.2	1	50.9	0.31
103	304	33.4	0.110	17	3	33.1	0	51.0	0.31
104	308	35.2	0.114	17	3	33.1	0	51.1	0.31
105	317	36.8	0.116	16	3	32.9	0	51.2	0.32
106	323	37.8	0.117	16	3	32.8	0	51.3	0.32
107	365	52.4	0.143	14	3	31.1	1	52.1	0.33
108	295	27.0	0.092	18	4	33.9	0	51.9	0.31
109	298	29.6	0.099	18	4	33.8	0	51.9	0.31
110	326	36.2	0.111	16	3	33.4	0	51.8	0.32
111	365	50.6	0.138	14	3	31.8	1	52.5	0.33
112	345	47.6	0.138	13	2	29.4	2	53.8	0.33
113	342	47.3	0.138	13	2	29.4	2	53.8	0.33
114	386	61.5	0.159	11	2	28.8	2	54.2	0.34
115	382	61.2	0.160	11	2	28.9	2	54.1	0.34
116	305	27.6	0.090	18	4	34.3	0	52.4	0.31
117	320	33.0	0.103	17	4	34.2	0	52.0	0.32
118	326	34.1	0.105	17	4	34.1	0	52.1	0.32
119	337	41.3	0.123	16	3	32.9	0	52.3	0.32
120	365	48.7	0.133	15	3	32.5	1	52.8	0.33
121	345	45.7	0.133	13	3	30.1	2	54.2	0.33
122	342	45.4	0.133	13	3	30.2	2	54.2	0.33
123	136	4.3	0.032	66	4	36.5	0	48.2	0.24
124	140	6.5	0.047	64	4	36.3	0	48.3	0.24
125	138	6.5	0.047	65	4	36.4	0	48.3	0.24
126	149	7.8	0.052	60	4	36.0	0	48.1	0.25
127	152	10.5	0.069	59	4	35.9	0	48.2	0.25
128	171	14.2	0.083	52	4	34.8	0	48.4	0.26
129	176	16.4	0.093	50	4	34.7	0	48.5	0.26
130	184	19.8	0.107	48	4	34.4	0	48.7	0.26

Design Nbr.	Disp (lton)	Margin (ltons)	Margin/Disp	FSR's	HSR's	Max Speed	Geo Sim	Acqu Cost ($M)	Scale
131	188	21.1	0.113	47	4	34.3	0	48.7	0.27
132	357	42.7	0.120	15	3	33.2	0	53.1	0.33
133	345	42.9	0.124	16	3	33.5	0	52.8	0.33
134	353	44.2	0.125	16	3	33.3	0	53.0	0.33
135	352	46.0	0.131	16	3	33.3	0	52.9	0.33
136	358	48.8	0.136	15	3	33.3	0	53.0	0.33
137	365	46.7	0.128	15	3	33.1	1	53.2	0.33
138	342	43.5	0.127	14	3	30.9	2	54.5	0.33
139	157	11.5	0.073	56	4	35.2	0	49.5	0.25
140	163	12.2	0.075	54	4	35.0	0	49.3	0.25
141	166	13.7	0.082	53	4	34.9	0	49.4	0.26
142	170	15.1	0.089	52	4	34.8	0	49.4	0.26
143	175	17.3	0.099	50	4	34.6	0	49.5	0.26
144	188	21.9	0.116	47	4	34.2	0	49.4	0.27
145	345	40.7	0.118	16	4	34.1	0	53.2	0.33
146	352	43.7	0.124	16	4	34.0	0	53.3	0.33
147	358	46.5	0.130	16	4	33.9	0	53.4	0.33
148	365	44.7	0.122	15	3	33.7	1	53.6	0.33
149	345	41.8	0.121	14	3	31.5	2	55.0	0.33
150	342	41.4	0.121	14	3	31.6	2	54.9	0.33
151	140	5.4	0.038	66	4	37.2	0	48.9	0.24
152	143	6.1	0.043	65	4	37.1	0	48.9	0.24
153	141	6.0	0.043	66	4	37.2	0	48.9	0.24
154	154	9.3	0.060	60	4	36.7	0	48.8	0.25
155	158	10.2	0.065	59	4	36.5	0	48.9	0.25
156	156	10.2	0.065	59	4	36.6	0	48.9	0.25
157	165	11.6	0.071	56	4	35.9	0	49.5	0.25
158	170	14.0	0.082	54	4	35.7	0	49.6	0.26
159	184	19.3	0.105	50	4	35.3	0	49.3	0.26
160	188	20.7	0.110	49	4	35.2	0	49.3	0.27
161	360	43.3	0.120	16	4	34.4	0	53.8	0.33
162	358	44.2	0.123	16	4	34.5	0	53.8	0.33
163	365	42.6	0.117	16	4	34.3	1	54.0	0.33
164	382	53.6	0.140	13	3	31.6	2	55.6	0.34
165	158	9.8	0.062	61	5	37.4	0	49.5	0.25
166	155	10.4	0.067	59	4	36.2	0	50.0	0.25
167	157	11.0	0.070	58	4	36.1	0	50.0	0.25
168	159	11.2	0.070	57	4	36.0	0	50.1	0.25
169	163	11.7	0.072	56	4	35.9	0	49.8	0.25
170	170	14.6	0.086	54	4	35.6	0	50.0	0.26
171	175	16.8	0.096	52	4	35.5	0	50.1	0.26
172	188	21.5	0.114	48	4	35.1	0	49.9	0.27
173	365	40.4	0.111	16	4	34.9	1	54.3	0.33
174	366	43.6	0.119	16	4	34.9	0	54.3	0.33

Design Nbr.	Disp (lton)	Margin (ltons)	Margin/Disp	FSR's	HSR's	Max Speed	Geo Sim	Acqu Cost ($M)	Scale
175	372	45.1	0.121	16	4	34.8	0	54.4	0.33
176	371	46.3	0.125	16	4	34.8	0	54.4	0.33
177	382	51.6	0.135	14	3	32.2	2	56.0	0.34
178	145	5.6	0.038	66	5	37.9	0	49.6	0.24
179	163	11.2	0.069	58	4	36.7	0	50.4	0.25
180	170	13.6	0.080	55	4	36.5	0	50.1	0.26
181	175	15.4	0.088	54	4	36.3	0	50.2	0.26
182	179	17.0	0.095	53	4	36.2	0	50.3	0.26
183	186	20.0	0.108	51	4	36.0	0	50.4	0.27
184	365	38.2	0.105	17	4	35.2	1	54.7	0.33
185	377	45.5	0.120	16	4	35.1	0	54.9	0.34
186	269	33.1	0.123	24	4	33.6	1	53.1	0.30
187	382	49.4	0.129	14	3	32.8	2	56.4	0.34
188	386	50.0	0.129	14	3	32.8	2	56.4	0.34
189	157	10.4	0.066	60	4	36.9	0	50.6	0.25
190	172	15.4	0.089	55	4	36.4	0	50.6	0.26
191	177	17.2	0.097	53	4	36.2	0	50.7	0.26
192	188	21.0	0.111	50	4	35.9	0	50.5	0.27
193	290	39.0	0.135	23	4	34.0	1	53.4	0.31
194	382	47.2	0.124	15	3	33.4	2	56.7	0.34
195	386	47.8	0.124	15	3	33.3	2	56.8	0.34
196	154	8.5	0.055	63	5	37.9	0	51.1	0.25
197	159	10.2	0.064	61	5	37.6	0	51.2	0.25
198	163	10.7	0.066	60	5	37.5	0	51.0	0.25
199	170	13.6	0.080	57	4	37.3	0	51.1	0.26
200	175	15.8	0.090	55	4	37.1	0	51.2	0.26
201	183	18.2	0.099	53	4	36.9	0	50.9	0.26
202	188	20.5	0.109	51	4	36.7	0	51.1	0.27
203	229	28.4	0.124	40	4	34.2	1	52.3	0.28
204	190	16.9	0.089	52	5	37.4	0	51.1	0.27
205	219	26.4	0.120	44	4	35.5	0	51.4	0.28
206	152	7.1	0.047	66	5	38.8	0	51.6	0.25
207	157	9.3	0.059	63	5	38.5	0	51.7	0.25
208	163	10.2	0.063	61	5	38.3	0	51.5	0.25
209	166	11.7	0.071	60	5	38.2	0	51.6	0.26
210	175	15.3	0.087	57	5	37.9	0	51.8	0.26
211	183	17.7	0.097	54	5	37.6	0	51.5	0.26
212	188	20.0	0.106	53	5	37.4	0	51.6	0.27
213	219	25.9	0.118	45	4	36.2	0	52.0	0.28
214	224	28.2	0.126	44	4	36.1	0	52.1	0.28
215	229	28.0	0.122	41	4	35.0	1	52.9	0.28
216	302	40.2	0.133	23	4	33.9	2	55.6	0.31
217	192	15.3	0.080	53	5	38.1	0	51.7	0.27
218	197	19.4	0.098	52	5	37.9	0	51.8	0.27

Design Nbr.	Disp (lton)	Margin (ltons)	Margin/Disp	FSR's	HSR's	Max Speed	Geo Sim	Acqu Cost ($M)	Scale
219	240	30.2	0.126	41	4	35.5	1	53.1	0.29
220	305	39.4	0.129	23	4	34.5	2	56.2	0.31
221	302	39.1	0.129	23	4	34.5	2	56.1	0.31
222	153	4.8	0.031	67	5	39.4	0	52.2	0.25
223	157	8.8	0.056	65	5	39.3	0	52.3	0.25
224	159	9.1	0.057	64	5	39.2	0	52.4	0.25
225	170	12.6	0.074	60	5	38.8	0	52.3	0.26
226	177	15.6	0.088	57	5	38.5	0	52.4	0.26
227	186	18.5	0.099	55	5	38.3	0	52.1	0.27
228	188	19.5	0.103	54	5	38.2	0	52.2	0.27
229	192	20.0	0.104	53	5	38.0	0	52.3	0.27
230	212	22.7	0.107	47	4	37.1	0	52.4	0.28
231	219	25.4	0.116	46	4	36.9	0	52.5	0.28
232	224	27.8	0.124	45	4	36.8	0	52.6	0.28
233	229	29.9	0.130	44	4	36.7	0	52.7	0.28
234	229	27.6	0.120	42	4	35.7	1	53.4	0.28
235	178	12.0	0.067	59	5	39.2	0	52.6	0.26
236	183	15.3	0.084	57	5	39.0	0	52.7	0.26
237	201	19.2	0.096	52	5	38.5	0	52.4	0.27
238	206	22.9	0.111	49	4	37.1	0	53.9	0.27
239	240	29.8	0.124	42	4	36.2	1	53.6	0.29
240	305	38.3	0.126	23	4	35.1	2	56.6	0.31
241	302	38.0	0.126	24	4	35.1	2	56.6	0.31
242	158	6.2	0.039	66	5	39.9	1	52.9	0.25
243	163	8.6	0.053	64	5	39.7	0	53.0	0.25
244	161	8.6	0.053	64	5	39.8	0	53.0	0.25
245	159	8.5	0.053	65	5	39.9	0	52.9	0.25
246	170	10.9	0.064	61	5	39.5	0	52.8	0.26
247	177	15.1	0.085	59	5	39.2	0	53.0	0.26
248	192	19.5	0.101	54	5	38.7	0	52.8	0.27
249	224	27.3	0.122	46	5	37.5	0	53.2	0.28
250	229	27.1	0.118	43	4	36.4	1	54.0	0.28
251	161	8.0	0.050	66	5	40.5	0	53.5	0.25
252	175	12.9	0.073	61	5	39.9	0	53.5	0.26
253	190	17.7	0.093	56	5	39.5	0	53.4	0.27
254	192	18.9	0.098	55	5	39.4	0	53.4	0.27
255	208	23.2	0.112	49	5	37.7	0	54.5	0.28
256	229	26.7	0.116	44	4	37.1	1	54.5	0.28
257	240	29.4	0.123	43	4	36.9	1	54.2	0.29
258	180	14.7	0.082	59	5	39.8	0	53.6	0.26
259	212	21.7	0.102	49	5	38.4	0	53.6	0.28
260	224	26.8	0.119	47	5	38.1	0	53.8	0.28
261	227	27.9	0.123	46	5	37.9	0	54.5	0.28
262	229	28.9	0.126	46	5	38.0	0	53.8	0.28

Design Nbr.	Disp (lton)	Margin (ltons)	Margin/Disp	FSR's	HSR's	Max Speed	Geo Sim	Acqu Cost ($M)	Scale
263	233	30.6	0.131	45	5	37.9	0	53.9	0.29
264	165	7.6	0.046	66	5	41.0	0	54.2	0.25
265	178	11.5	0.065	61	5	40.5	1	54.1	0.26
266	180	14.2	0.079	60	5	40.4	0	54.2	0.26
267	185	14.6	0.079	59	5	40.2	0	54.3	0.26
268	196	18.6	0.095	55	5	39.9	0	54.0	0.27
269	212	21.2	0.100	51	5	39.1	0	54.1	0.28
270	224	26.3	0.117	48	5	38.7	0	54.3	0.28
271	229	26.2	0.114	45	5	37.7	1	55.1	0.28
272	240	28.9	0.121	44	5	37.5	1	54.8	0.29
273	227	27.4	0.121	47	5	38.5	0	55.1	0.28
274	229	28.4	0.124	47	5	38.6	0	54.4	0.28
275	233	30.1	0.129	46	5	38.5	0	54.5	0.29
276	240	28.5	0.119	44	5	38.1	1	55.3	0.29
277	265	34.1	0.129	37	4	35.3	2	57.5	0.30
278	168	7.0	0.042	67	5	41.3	0	54.8	0.26
279	167	7.0	0.042	68	5	41.3	0	54.8	0.26
280	176	8.3	0.047	64	5	41.0	0	54.7	0.26
281	183	13.8	0.075	62	5	40.7	0	54.8	0.26
282	187	14.1	0.076	60	5	40.6	0	54.9	0.27
283	188	14.3	0.076	60	5	40.5	0	54.9	0.27
284	185	14.1	0.076	61	5	40.6	0	54.9	0.26
285	199	18.2	0.092	57	5	40.2	0	54.7	0.27
286	219	23.5	0.107	51	5	39.3	0	54.8	0.28
287	229	27.9	0.122	49	5	39.0	0	55.0	0.28
288	229	25.7	0.112	46	5	38.3	1	55.7	0.28
289	206	20.7	0.101	54	5	39.5	0	56.1	0.27
290	240	28.0	0.117	46	5	38.6	1	55.9	0.29
291	267	33.7	0.126	38	4	35.9	2	58.1	0.30
292	265	33.7	0.127	38	4	35.9	2	58.0	0.30
293	229	27.4	0.119	53	5	39.0	0	55.5	0.28
294	265	33.2	0.125	39	4	36.5	2	58.6	0.30
295	265	32.7	0.123	41	4	36.9	2	59.2	0.30

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```
      PROGRAM MAIN
C*************************************************************************
C    This is the main program for Multi-Objective Evolutionary Program (EP)
C      for Large Scale Vehicle II.
C
C     Programmer:  Allan Andrew  5/5/98
C*************************************************************************

       IMPLICIT NONE

       INCLUDE 'VARIABLES.F'

C      Open file for base-10 population characteristics after last generation.
       OPEN (UNIT=21, FILE='POPLN2.OUT', STATUS='NEW')
C      Open file for binary population characteristics after last generation.
       OPEN (UNIT=22, FILE='BIPOP2.OUT', STATUS='NEW')
C      Open file for base-10 population characteristics for restart.
C      OPEN (UNIT=30, FILE='POPLN3.OUT', STATUS='OLD')
C      Open file for count of number of non-dominated designs.
       OPEN (UNIT=32, FILE='NUM_ND.OUT', STATUS='NEW')
C      Open file for characteristics of non-dominated designs found.
       OPEN (UNIT=41, FILE='NON_DOM2.OUT', STATUS='NEW')
C      Open file for characteristics of non-dominated designs previously found.
       OPEN (UNIT=51, FILE='NON_DOM3.OUT', STATUS='OLD')
C      Open file of non-dominated designs previously found using exhaustive
search.
       OPEN (UNIT=71, FILE='EXH_SEARCH.OUT', STATUS='OLD')
C      Open file to record number of non-dominated designs found in EP search
that were also found in exhaustive search.
       OPEN (UNIT=72, FILE='NBR_FOUND.OUT', STATUS='NEW')
C      Open file to mark start time.
       OPEN (UNIT=80, FILE='START_TIME.OUT', STATUS='NEW')

       READ (71,*) EXH_SEARCH_NUM

       DO I=1, 326
             READ (71, 7040) (EXH_SEARCH(J, I), J=1,3)
       END DO


C     Generate the RANG array by assigning parameter values to the array.
      CALL RNGGEN (DMIN,DMAX,LDMIN,LDMAX,NFMIN,NFMAX,NAMIN,NAMAX,
     *             BTMIN,BTMAX,BPMIN,BPMAX,COTMIN,COTMAX,SONMIN,SONMAX,
     *             DNUM,LDNUM,NFNUM,NANUM,BTNUM,BPNUM,COTNUM,SONNUM,
     *             VARNUM,RANG)


C     USEOLD_NON_DOM =.TRUE. forces program to begin from a previously
C      defined non-dominated array.
       USEOLD_NON_DOM = .true.

       IF (USEOLD_NON_DOM) THEN
             READ (51, *) NUM_NON_DOM
c      PRINT *, 'NUM-NON_DOM = ', NUM_NON_DOM
             DO I=1, NUM_NON_DOM
                   READ (51, 7020) (NON_DOM (J,I),J=1,NUM_POP_CHAR)
             END DO

       ELSE
             NUM_NON_DOM = 0

       END IF

C      Set the following line to restart the EP more than once.
       DO 4000 RUN_NUM=1, 1
```

```
C     USEOLD_POPLN=.TRUE. forces program to begin from a previously defined
C       generation.  Otherwise the population is selected randomly.
      USEOLD_POPLN=.FALSE.

              GEN_NUM = 1
              ADD_TNUM = 0
              REMOVE_TNUM  = 0

C     Generate a random population
         DO 220  I=1, GENSIZ
                    DO 200 J=1, GENEL
                          X = ran2(IDUM)
                          GENE(J) = NINT(X)
 200                CONTINUE

C             Translate the gene from binary to base 10.
                    CALL DECODE (GENE, GENEL, RANG, VARNUM, MBR)

C             Balance the individual member to ensure a feasible design.
                    CALL BALANCE (MBR, BALANCE_OUT, WCOST)

C             Calculate the Measures of Performance (MOPs)
                    CALL CALC_MOPS (MBR, BALANCE_OUT,
     *                                    FR_SPD_RUNS, HI_SPD_RUNS, VMAX,
     *                                    VMAX_HA, SCALE)
C             Calculate discounted total ownership cost and acquisition cost.
                    CALL COST (MBR, WCOST, BALANCE_OUT, DTOC, ACQU_COST)

C             Calculate the Measures of Effectiveness
                    CALL CALC_HA_MOE (VMAX_HA, HI_SPD_RUNS, MBR,
     *                                          HAMOE)
                    CALL CALC_HD_MOE (MBR, BALANCE_OUT, FR_SPD_RUNS,
     *                                          HDMOE, GEO)

C             Assign characteristics and output of BALANCE, CALC_MOPS
C              COST, HDMOE and HAMOE to the population array.
C              HDMOE is made negative so that all comparisons are made with
C              lower values preferred.
       CALL   REPLACE (BIPOP, GENE, GENEL, POPLN, NUM_POP_CHAR,
     *                     GENSIZ, I, DTOC, HAMOE,
     *                     HDMOE, MBR, VARNUM, BALANCE_OUT, FR_SPD_RUNS,
     *                     HI_SPD_RUNS, VMAX, GEO, ACQU_COST, GEN_NUM,
     *                            GEN_NUM_MAX, RUN_NUM, MBR_CHAR,
     *                            VMAX_HA, SCALE)

C      Determine if the member is non-dominated.
       CALL NON_DOMINATED (MBR_CHAR, NUM_POP_CHAR, NON_DOM,
     *                            NUM_NON_DOM_MAX, NUM_NON_DOM,
     *                            ADD_TNUM, REMOVE_TNUM, EXH_SEARCH)

 220          CONTINUE

       PRINT *, 'GENERATION # 1'
       PRINT *, 'ADD', ADD_TNUM
       PRINT *, 'REMOVE', REMOVE_TNUM

C      Start genetic algorithm for required number of generations.
       DO 2000 GEN_NUM = 2, GEN_NUM_MAX
              PRINT *,'RUN#/GENERATION # =', RUN_NUM,GEN_NUM
C             WRITE (21,*)
C             WRITE (21, *) 'GEN_NUM =', GEN_NUM

              ADD_TNUM = 0
              REMOVE_TNUM = 0
```

```
C      One generation consists of finding a GENSIZ number of offspring.
       DO 1000 MATE_NUM = 1, GENSIZ/2

C      Select two members of the population to be parents and two
C      members to be removed from the population.
      CALL TOURNAMENT (POPLN, NUM_POP_CHAR, GENSIZ, IDUM, PARENT, KILL)

C      Crossover and mutate the two parents to create two new members
C             of the population.
       CALL MATE (PARENT, BIPOP, GENEL,
     *              GENSIZ, GEN_NUM,
     *              GEN_NUM_MAX, IDUM, BI_CHILD1, BI_CHILD2)

C      Decode the binary information into base 10, balance
C       and calculate MOP's, cost, and MOE's for CHILD1 and CHILD2.
C      Replace the lethals with the children in the population array and
C             binary population array.

       CALL DECODE (BI_CHILD1, GENEL, RANG, VARNUM, CHILD1)
       CALL BALANCE (CHILD1, BALANCE_OUT, WCOST)
       CALL CALC_MOPS (CHILD1, BALANCE_OUT, FR_SPD_RUNS,
     *                    HI_SPD_RUNS, VMAX, VMAX_HA, SCALE)
       CALL COST (CHILD1, WCOST,BALANCE_OUT, DTOC, ACQU_COST)
       CALL CALC_HA_MOE (VMAX_HA, HI_SPD_RUNS, CHILD1, HAMOE)
       CALL CALC_HD_MOE (CHILD1, BALANCE_OUT, FR_SPD_RUNS,HDMOE, GEO)
       CALL REPLACE (BIPOP, BI_CHILD1, GENEL, POPLN, NUM_POP_CHAR,
     *                    GENSIZ, KILL(1), DTOC, HAMOE,
     *                    HDMOE, CHILD1, VARNUM, BALANCE_OUT, FR_SPD_RUNS,
     *                    HI_SPD_RUNS, VMAX, GEO, ACQU_COST,
     *                    GEN_NUM,     GEN_NUM_MAX, RUN_NUM, CHILD1_CHAR,
     *                    VMAX_HA, SCALE)
C      WRITE (21, 7020) CHILD1_CHAR
C      WRITE (21, 7020) (POPLN(J, KILL(1)), J=1, NUM_POP_CHAR)
C      WRITE (21,*)
       CALL NON_DOMINATED (CHILD1_CHAR, NUM_POP_CHAR,
     *                           NON_DOM, NUM_NON_DOM_MAX, NUM_NON_DOM,
     *                           ADD_TNUM, REMOVE_TNUM, EXH_SEARCH)


       CALL DECODE (BI_CHILD2, GENEL, RANG, VARNUM, CHILD2)
       CALL BALANCE (CHILD2, BALANCE_OUT, WCOST)
       CALL CALC_MOPS (CHILD2, BALANCE_OUT, FR_SPD_RUNS,
     *                    HI_SPD_RUNS, VMAX, VMAX_HA, SCALE)
       CALL COST (CHILD2, WCOST, BALANCE_OUT, DTOC, ACQU_COST)
       CALL CALC_HA_MOE (VMAX_HA, HI_SPD_RUNS, CHILD2, HAMOE)
       CALL CALC_HD_MOE (CHILD2, BALANCE_OUT, FR_SPD_RUNS,HDMOE, GEO)
       CALL REPLACE (BIPOP, BI_CHILD2, GENEL, POPLN, NUM_POP_CHAR,
     *                    GENSIZ, KILL(2), DTOC, HAMOE,
     *                    HDMOE, CHILD2, VARNUM, BALANCE_OUT, FR_SPD_RUNS,
     *                    HI_SPD_RUNS, VMAX, GEO, ACQU_COST,
     *                    GEN_NUM, GEN_NUM_MAX, RUN_NUM, CHILD2_CHAR,
     *                    VMAX_HA, SCALE)
C      WRITE (21, 7020) CHILD2_CHAR
C      WRITE (21, 7020) (POPLN(J, KILL(2)), J=1, NUM_POP_CHAR)
C      WRITE (21, *)
       CALL NON_DOMINATED (CHILD2_CHAR, NUM_POP_CHAR,
     *                           NON_DOM, NUM_NON_DOM_MAX, NUM_NON_DOM,
     *                           ADD_TNUM, REMOVE_TNUM, EXH_SEARCH)


 1000  CONTINUE

       PRINT *, 'ADD', ADD_TNUM
       PRINT *, 'REMOVE', REMOVE_TNUM
       PRINT *, 'NUM-NON-DOM', NUM_NON_DOM

       WRITE (32,*) GEN_NUM, ADD_TNUM, REMOVE_TNUM, NUM_NON_DOM
```

```
C      Adjust the cost and MOE's to compensate for infeasible designs.
       CALL ADJUST_MOES (POPLN, NUM_POP_CHAR, GENSIZ,
     *                            GEN_NUM, GEN_NUM_MAX)

 2000  CONTINUE

 3000  WRITE (21, 7020) POPLN

       WRITE  (22,7000) BIPOP

       WRITE (41, *) NUM_NON_DOM
       DO I=1, NUM_NON_DOM
             WRITE (41, 7020) (NON_DOM (J,I),J=1,NUM_POP_CHAR)
       END DO

 4000 CONTINUE

 7000 FORMAT (28(I3))
 7010 FORMAT (I5, 3(F9.2))
 7020 FORMAT (27(F10.3))
 7030  FORMAT (8(F10.3))
 7040 FORMAT (3(F10.3))

      END    PROGRAM MAIN
```

```
C*************************************************************************
C      VARIABLE.F assigns variable types and parameter values for use by
C                 main program.
C       Programmer Allan Andrew  5/5/98
C*************************************************************************

      INTEGER ADD_TNUM, BPNUM,  BTMAX,  BTMIN,  BTNUM,  CONVERGE,
     *            COTNUM,      DNUM,  FR_SPD_RUNS,
     *            GENEL, GEN_NUM,
     *            GEN_NUM_MAX, GENSIZ,      GEO,
     *            HI_SPD_RUNS, I,           IDUM,  J,     KILL(2),
     *            LDNUM, MATE_NUM,    NANUM,
     *            NFNUM, NUM_NON_DOM,
     *            NUM_NON_DOM_MAX,    NUM_POP_CHAR,
     *            PARENT(2),   REMOVE_TNUM, RUN_NUM,
     *            SONMAX, SONMIN,     SONNUM,      VARNUM



      REAL   ACQU_COST,   BPMAX,  BPMIN, COTMAX, COTMIN,   DMAX,  DMIN,
     *       DTOC,  HAMOE, HDMOE, LDMAX, LDMIN, NAMAX, NAMIN,
     *        NFMAX,       NFMIN, ran2,  SCALE,      VMAX,
     *       VMAX_HA,      WCOST(7),    X

      LOGICAL USEOLD_NON_DOM,    USEOLD_POPLN


C***VARIABLE SUMMARY*****************************************************
C
C      *MAX - Maximum value for variable
C      *MIN - Minimum value for variable
C      *NUM - Number of binary place holders set aside in the gene for variable
C         A1WEIGHT - A1 weight of LSV with exception of propulsor
C       ACQU_COST - Acquisition cost ($K)
C       ADD_TNUM - The total added to non_dom array each generation
C      BP* - Battery Power
C      BT* - Battery Type
C      COT* - Hull coating
C      D* - Hull Diameter
C       DTOC - Discounted Total Ownership cost calculated by COST subprogram
C      GENEL - Length of the binary gene string
C       GEN_NUM      - The number of the current generation
C       GEN_NUM_MAX - The maximum number of allowed generations.
C      GENSIZ - Number of individuals in the population, i.e. generation size
C       GEO - Integer that represents the geo-similitude of the member
C                 0=None  1=SSN-21          2=NSSN
C       FR_SPD_RUNS - Number of runs possible at Froude scaled speed
C       HAMOE - Hydro-acoustic Measure of Effectiveness
C       HDMOE - Hydrodynamic Measure of Effectiveness
C       HI_SPD_RUNS - Number of runs at 100%, 90%, 80%... max speed
C      I,J - Integer for loop counting
C      IDUM - Seed value for random number generator (Negative integer)
C       KILL - represents the 2 members of the population array that are
C                 designated for removal
C      LD* - Length to Diameter Ratio
C       MATE_NUM - The number of times members of the population have mated
C                          during the current generation
C      NA* - Shape factor aft
C      NF* - Shape factor forward
C       Parent - represents the 2 members of the population array that are
C                 designated for mating
C       REMOVE_TNUM - The total number removed from non_dom array each
C       generation
C       RUN_NUM - The number in the current series of runs
C        SON* - Lake sonar system
C       TOOLONG - The stack length of the equipment and tanks is longer than
C       the hull
```

```
C      TOOHEAVY - The weight of the ship is greater than the displacement
C     USEOLD* - Logical variable to determine if old input data should be
C      used, or if new data should be generated to start the first generation
C     VARNUM - Number of variables in input
C      VMAX - maximum LSV speed
C      VOLSUB - Total of hull volume and coating submerged to operating depth
C      WCOST - Seven weights to be used to calculate cost
C      WPROP - Weight of the propulsor
C     X - Variable returned from random number generator
C
C************************************************************************

C      Seeds used for the random number generator:
c       DATA IDUM /-2589/
       DATA IDUM /-4658/
C      DATA IDUM /-5346/
C      DATA IDUM /-9745/
C      DATA IDUM /-1896/


      PARAMETER (DMIN=8.0,     DMAX=15.0,   LDMIN=6.0,     LDMAX=13.0,
     *    .       NFMIN=1.75,  NFMAX=4.00,  NAMIN=1.75,    NAMAX=4.00,
     *            BTMIN=1,     BTMAX=4,     BPMIN=3000.0, BPMAX=6500.0,
     *            COTMIN=0.0,  COTMAX=3.5,  SONMIN=1,      SONMAX=2,
     *            DNUM=3,      LDNUM=3,     NFNUM=3,       NANUM=3,
     *            BTNUM=2,     BPNUM=4,     COTNUM=3,      SONNUM=1,
     *            VARNUM=8,    GENEL=22,    GENSIZ=200,
     *           NUM_POP_CHAR=27,               GEN_NUM_MAX = 160,
     *           NUM_NON_DOM_MAX = 5000)

      REAL        BALANCE_OUT(7),CHILD1(VARNUM),     CHILD2(VARNUM),
     *              EXH_SEARCH(3,184),
     *              NON_DOM (NUM_POP_CHAR, NUM_NON_DOM_MAX),
     *              MBR (VARNUM),MBR_CHAR(NUM_POP_CHAR),
     *              CHILD1_CHAR(NUM_POP_CHAR),CHILD2_CHAR(NUM_POP_CHAR),
     *              POPLN (NUM_POP_CHAR,GENSIZ),
     *              RANG(VARNUM,3)

      INTEGER       BI_CHILD1(GENEL),   BI_CHILD2(GENEL),
     *              BIPOP (GENEL,GENSIZ),      GENE (GENEL)

C      BI_CHILD* - A child represented in binary form produced by
C                       the mating of two parents
C     BIPOP - An array of the binary code of each member of the population
C     GENE is the binary string that represents a member of the population
C     CHILD1(2) - Base 10 format of the binary string for child 1 or 2
C     MBR is the base 10 format of the binary string
C      MBR_CHAR - The list of characteristics for each member randomly
C             generated
C      CHILD1(2)_CHAR - The list of characteristics for each member generated
C             child
C     RANG is a 2-dimensional array that holds the min, max and length of
C       the input variables
```

```
      SUBROUTINE RNGGEN (DMIN,DMAX,LDMIN,LDMAX,NFMIN,NFMAX,NAMIN,NAMAX,
     *             BTMIN,BTMAX,BPMIN,BPMAX,COTMIN,COTMAX,SONMIN,SONMAX,
     *             DNUM,LDNUM,NFNUM,NANUM,BTNUM,BPNUM,COTNUM,SONNUM,
     *             VARNUM,RANG)


C*************************************************************************
C     RNGGEN assigns values to RANG, a 2-dimensional array that holds the
C       min value, max value and binary length of the input variables.
C     Programmer:  Allan Andrew  5/5/98
C***************************************************************************



      INTEGER DNUM,   LDNUM,  NFNUM,  NANUM,  BTNUM,  BPNUM,
     *        COTNUM, SONNUM, BTMIN,  BTMAX,  SONMIN, SONMAX, VARNUM

      REAL    DMIN,   DMAX,   LDMIN,  LDMAX,  NFMIN,  NFMAX,  NAMIN,
     *        NAMAX,  BPMIN,  BPMAX,  COTMIN, COTMAX

      REAL       RANG (VARNUM,3)


      RANG(1,1)=DMIN;        RANG(1,2)=DMAX;        RANG(1,3)=DNUM
      RANG(2,1)=LDMIN;        RANG(2,2)=LDMAX;        RANG(2,3)=LDNUM
      RANG(3,1)=NFMIN;        RANG(3,2)=NFMAX;        RANG(3,3)=NFNUM
      RANG(4,1)=NAMIN;        RANG(4,2)=NAMAX;        RANG(4,3)=NANUM
      RANG(5,1)=BTMIN;        RANG(5,2)=BTMAX;        RANG(5,3)=BTNUM
      RANG(6,1)=BPMIN;        RANG(6,2)=BPMAX;        RANG(6,3)=BPNUM
      RANG(7,1)=COTMIN;        RANG(7,2)=COTMAX;        RANG(7,3)=COTNUM
      RANG(8,1)=SONMIN;        RANG(8,2)=SONMAX;        RANG(8,3)=SONNUM

       RETURN
      END SUBROUTINE RNGGEN
```

```
        FUNCTION ran2(idum)

C*****************************************************************************
C     RAN2 returns a real variable with uniform distribution between 0 and 1.
C       It was taken from the MIT FORTRAN recipes library on ATHENA.
C*****************************************************************************


      INTEGER idum,IM1,IM2,IMM1,IA1,IA2,IQ1,IQ2,IR1,IR2,NTAB,NDIV
      REAL ran2,AM,EPS,RNMX
      PARAMETER (IM1=2147483563,IM2=2147483399,AM=1./IM1,IMM1=IM1-1,
     *IA1=40014,IA2=40692,IQ1=53668,IQ2=52774,IR1=12211,IR2=3791,
     *NTAB=32,NDIV=1+IMM1/NTAB,EPS=1.2e-7,RNMX=1.-EPS)
      INTEGER idum2,j,k,iv(NTAB),iy
      SAVE iv,iy,idum2
      DATA idum2/123456789/, iv/NTAB*0/, iy/0/
      if (idum.le.0) then
        idum=max(-idum,1)
        idum2=idum
        do 11 j=NTAB+8,1,-1
          k=idum/IQ1
          idum=IA1*(idum-k*IQ1)-k*IR1
          if (idum.lt.0) idum=idum+IM1
          if (j.le.NTAB) iv(j)=idum
11      continue
        iy=iv(1)
      endif
      k=idum/IQ1
      idum=IA1*(idum-k*IQ1)-k*IR1
      if (idum.lt.0) idum=idum+IM1
      k=idum2/IQ2
      idum2=IA2*(idum2-k*IQ2)-k*IR2
      if (idum2.1t.0) idum2=idum2+IM2
      j=1+iy/NDIV
      iy=iv(j)-idum2
      iv(j)=idum
      if(iy.lt.1)iy=iy+IMM1
      ran2=min(AM*iy,RNMX)
      return
      END

C*****************************************************************************
```

```
      SUBROUTINE DECODE (GENE, GENEL, RANG, VARNUM, MBR)

C*****************************************************************************
C     DECODE takes the binary gene and translates it into a base 10 string.
C      5/5/98
C*****************************************************************************
      IMPLICIT NONE

      INTEGER  I, J, K, POSIT, GENEL, ORD, VALNUM, VARNUM, GENE(GENEL)
C       ORD - Conversion of the binary string for each variable to base 10
C       VALNUM - Number of values for each variable
C       POSIT - Position in the binary string of an individual variable

      REAL    RANG (VARNUM,3), MBR(VARNUM)


C             PRINT 7000, GENE

      J=1
      K=0
      DO 200 I=1, VARNUM
         ORD=0
         POSIT=1
          K = K + RANG(I,3)

 100     IF (J.LE.K) THEN
                ORD = ORD + (2**(POSIT-1))*GENE(J)
                 POSIT = POSIT +1

                J = J+1
                GO TO 100
         END IF

         VALNUM=2**(RANG(I,3))

       MBR(I)=RANG(I,1) + ORD*(RANG(I,2) - RANG(I,1))/(VALNUM-1)

 200  CONTINUE

 7000 FORMAT (22 I3)
 7010 FORMAT (8(F9.2))

      RETURN
      END
```

```
      SUBROUTINE BALANCE (MBR, BALANCE_OUT, WCOST)

C*************************************************************************
C     BALANCE takes a member of the population, determines if the member is a
C       feasible design, and returns member attributes.
C       Programmer:  Allan Andrew 5/5/98
C**************************************************************************
      IMPLICIT NONE

      REAL    A1LCG, A1VCG, A1WEIGHT, BALANCE_OUT(7), BP, COT, D, LBATT,
     *        LCB, LCGMBT, LD, LMBTA, LMBTF, LTRIM, NF, NA,
     *        VOLSUB, VOLTRIM, WSCOT,    WCOST(7),
     *        WSHULL, WPROP

      INTEGER BT

      LOGICAL TOOLONG, TOOHEAVY

C     A1LCG - Longitudinal center of gravity in condition A1 with propulsor
C            excluded
C     A1VCG - Vertical center of gravity  with propulsor, hull coating and
C            lead excluded
C     A1WEIGHT - A1 weight of LSV with exception of propulsor
C     LBATT - Length of the battery
C     LCB - Longitudinal center of buoyancy
C     LCGMBT : Longitudinal Center of Gravity for filled MBT'S
C     LMBTA, LMBTF - Length of MBT aft and forward
C     LTRIM : Length of the trim tank
C     TOOLONG - The stack length of the equipment and tanks is longer than
C            the hull
C     TOOHEAVY - The weight of the ship is greater than the displacement
C     VOLSUB - Total of hull volume and coating submerged to operating depth
C     VOLMBTA, VOLMBTF - Volume of MBT's aft and forward
C     VOLTRIM - Volume of the trim tank
C     WSHULL - Wetted surface area
C     WPROP - Weight of the propulsor

      REAL MBR(8)

C     Assign input parameters from input arrays.
      D = MBR(1)
      LD = MBR(2)
      NF = MBR(3)
      NA = MBR(4)
      BT = NINT (MBR(5))
      BP = MBR(6)
      COT = MBR(7)

      CALL CALC_GEOMETRY (D, LD, NA, NF, COT,          VOLSUB, LCB,
     *                           WSHULL, WSCOT, LMBTF, LMBTA, LTRIM, LCGMBT,
     *                           VOLTRIM)

      CALL CALC_WEIGHT (D, LD, LMBTF, LMBTA, BT, BP, COT, WSHULL,
     *                                  A1WEIGHT, A1LCG, A1VCG, LBATT, WCOST)

      CALL DET_FEAS (D, LD, LMBTF, LBATT, LTRIM, LMBTA, VOLSUB, LCB,
     *                    A1WEIGHT, A1LCG, LCGMBT, TOOLONG, TOOHEAVY, WPROP)

C     Assign output parameters to output array.
      BALANCE_OUT(1) = VOLSUB/36.0
      BALANCE_OUT(2) = A1WEIGHT
      BALANCE_OUT(3) = WPROP

     IF (TOOLONG) THEN
            BALANCE_OUT(4) = 1
      ELSE
            BALANCE_OUT(4) = 0
```

```
      END IF

      IF (TOOHEAVY) THEN
             BALANCE_OUT(5) = 1
      ELSE
             BALANCE_OUT(5) = 0
      END IF

      BALANCE_OUT(6) = WSCOT
      BALANCE_OUT(7) = VOLTRIM

      RETURN
      END    SUBROUTINE BALANCE


C*****************************************************************************
C     DET_FEAS determines the feasibility of the design by ensuring the
C            length of all equipment fits in the hull and the weight is less
C            than the displacement.  It also determines the maximum propeller C
      weight.
C*****************************************************************************
      SUBROUTINE DET_FEAS (D, LD, LMBTF, LBATT, LTRIM, LMBTA,VOLSUB,LCB,
     *                     A1WEIGHT, A1LCG, LCGMBT, TOOLONG, TOOHEAVY, WPROP)

      IMPLICIT NONE

      REAL  A1LCG, A1WEIGHT, CONST, D, L, LCB, LD, LMBTF, LBATT,
     *       LCGLEAD,LCGMBT, LCOMP, LTRIM, LMBTA, SUBDISP,
     *       VOLSUB, WLEAD,WPROP


      LOGICAL TOOLONG, TOOHEAVY
C     CONST - A place-holder representing constants in the propeller weight
C            calculation
C     LCGLEAD - Longitudinal center of gravity of the lead
C     LCOMP - Total component stack length
C     WLEAD - Weight of ballast and trim lead

C     Calculate the total length of the MBT's, trim tank, battery, propulsion
C            motor and shafting (13ft), propulsion motor controller (12ft) and
C            electronic cabinets (12ft).

      L = D*LD

      LCOMP = LMBTF + LBATT + LTRIM + LMBTA + 37

      IF (L .LT. LCOMP) THEN
             TOOLONG = .TRUE.
      ELSE
             TOOLONG = .FALSE.
      END IF

C     Calculate the LSV displacement from submerged volume (freshwater 36
C            cubic ft / ton)and determine if the LSV weighs more than it C
             displaces.

      SUBDISP = VOLSUB / 36.0

C     Calculate the maximum propulsor weight that can be carried.  Assume all
C            lead can be placed 5 feet aft of forward perpendicular.

      LCGLEAD = 5.0
      CONST = SUBDISP*LCB - A1WEIGHT*A1LCG - 0.1*SUBDISP*LCGMBT

      WPROP = (CONST - (SUBDISP-A1WEIGHT/0.9)*LCGLEAD)/(L-LCGLEAD)

      IF (WPROP .LT. 0.0) THEN
```

```
              TOOHEAVY = .TRUE.
        ELSE
              TOOHEAVY = .FALSE.
        END IF

        WLEAD = SUBDISP - A1WEIGHT/0.9 - WPROP

        END   SUBROUTINE DET_FEAS

C***************************************************************************
C       CALC_GEOMETRY calculates the volume, longitudinal center of buoyancy,
C             longitudinal center of gravity of main ballast tanks and
C             wetted surface area.
C***************************************************************************

        SUBROUTINE   CALC_GEOMETRY (D, LD, NA, NF, COT, VOLSUB, LCB,
     *                       WSHULL, WSCOT, LMBTF, LMBTA, LTRIM, LCGMBT,
     *                       VOLTRIM)

        IMPLICIT NONE

        REAL COT, D, DCOT, DISPCHANGE, DISPSURF, DISPSUB, L,LA,LCB,LCGMBT,
     *        LCGMBTA, LCGMBTF, LF,LMBTA, LMBTF, LPMB, LD, LTRIM,
     *        MOMMBTA, MOMMBTF, NA, NF, PI, VMOMA, VMOMF, VMOMPMB, VOLA,
     *        VOLAI, VOLF, VOLFI, VOLPMB,       VOLMBTA, VOLMBTF,VOLMOM,
     *        VOLHULL, VOLCOT, VOLSURF, VOLSUB, VOLTRIM, WSHULL, WSA,
     *        WSF, WSPMB, WSCOT, WSFCOT, WSPMBCOT, WSACOT




        INTEGER DIVF, DIVA, I

C       VARAIBLE DESCRIPTIONS
C             DCOT : Diameter with hull coating
C             DISPSURF,DISPSUB,DISPCHANGE : Displacement on surface, submerged
C                   and change between
C                   surface and operating depth
C             L : Overall Length
C             LA : Length aft
C             LCGMBTA, LCGMBTF : Longitudinal Center of Gravity for filled aft
C                   and forward MBT
C             LF : Length forward
C             LPMB : Length of parallel mid-body
C             MOMMBTA, MOMMBTF : Moment of aft and forward MBT
C             RA,RF : Radii of LSV at points of XA and XF
C             RACOT,RFCOT : Radii of LSV at points of XA and XF with coating
C             VMOMA, VMOMF, VMOMPMB : Volume moment aft, forward, and PMB
C             VOLA, VOLF, VOLPMB : Volume of aft, forward, and parallel
C                                                 mid-body
C             VOLAI, VOLFI : Volume of the ith portion of the aft,
C                                                 forward, or PMB
C             VOLMOM : Total volume moment
C             VOLCOT : Volume of the hull coating on surface
C             VOLSUB : Volume of LSV with fully compressed hull coating
C             VOLSURF : Volume of LSV on surface with uncompressed hull coating
C             VOLHULL :  Volume of hull without coating
C             XA : Distance from stem for aft portion of LSV
C             XF : Distance from stem for forward portion of LSV
c            *COT : Variable with hull coating


        PARAMETER (PI=3.1415926, DIVF=100, DIVA=100)

        REAL XA(DIVA), XF(DIVF), RA(DIVA),RACOT(DIVA),
     *        RF(DIVF), RFCOT(DIVF)
```

```
      L=LD*D
      LF=2.4*D
      LA=3.6*D
      LPMB=L-LF-LA
      DCOT = D + 2.0*COT/12

C     Determine longitudinal points to be evaluated
      DO 100 I=1, DIVF
            XF(I) = (I-1)*(LF/(DIVF-1))
            RF(I) = (D/2.0) * ((1.0 - ((LF-XF(I))/LF))**(1.0/NF))
            RFCOT(I) = (DCOT/2.0) * ((1.0 - ((LF-XF(I))/LF))**(1.0/NF))
100   CONTINUE

C     PRINT *, 'RF = ',RF

      DO 200 I=1, DIVA
            XA(I) = LF + LPMB + LA*(I-1)/(DIVA-1)

            IF ( (XA(I)-LF-LPMB) .LT. 0.0) THEN
                        RA(I) = D/2.0
                        RACOT(I) = DCOT/2.0
                  ELSE
                        RA(I) = (D/2.0) * ( 1- (((XA(I)-LF-LPMB) / LA)**NA))
                        RACOT(I) = (DCOT/2.0)*( 1- (((XA(I)-LF-
     *                            LPMB)/LA)**NA))
            END IF

200   CONTINUE
C     PRINT *, 'RA = ',RA

C     Calculate volumes, volume moments and wetted surface areas
C           forward, aft and parallel mid-body

      VOLF = 0
      VMOMF = 0
      WSF = 0
      WSFCOT = 0
      DO 300 I=1, DIVF-1
            VOLFI = (PI/4) * ((RF(I)+RF(I+1))**2) * (XF(I+1)-XF(I))
            VOLF = VOLF + VOLFI
            VMOMF = VMOMF + VOLFI * ( XF(I+1) + XF(I) ) / 2
            WSF = WSF + PI * (RF(I)+RF(I+1)) * (XF(I+1)-XF(I))
            WSFCOT = WSFCOT + PI * (RFCOT(I)+RFCOT(I+1)) * (XF(I+1)-XF(I))
300   CONTINUE

      VOLA = 0
      VMOMA = 0
      WSA = 0
      WSACOT = 0
      DO 400 I=1, DIVA-1
            VOLAI = (PI/4) * ((RA(I)+RA(i+1))**2) * (XA(I+1)-XA(I))
            VOLA = VOLA + VOLAI
            VMOMA = VMOMA + VOLAI *  (LF + LPMB + (XF(I+1)+XF(I))/2)
            WSA = WSA + PI * (RA(I)+RA(i+1)) * (XA(I+1)-XA(I))
            WSACOT = WSACOT + PI * (RACOT(I)+RACOT(i+1)) * (XA(I+1)-XA(I))
400   CONTINUE

      VOLPMB = (PI/4) * (D**2) * LPMB
      VMOMPMB = VOLPMB * (LF + LPMB/2)
      WSPMB = PI * D * LPMB
      WSPMBCOT = PI * DCOT * LPMB


C     Calculate total volume, volume moment, LCB and wetted surface area
      VOLHULL = VOLF + VOLA + VOLPMB
      VOLMOM = VMOMF + VMOMA + VMOMPMB
```

```
      LCB = VOLMOM / VOLHULL
      WSHULL = WSF + WSPMB + WSA
      WSCOT = WSFCOT + WSPMBCOT + WSACOT

C     Calculate the volume of the hull coating and the LSV
C           volume surfaced and submerged.  Assume that the
C           hull coating compresses to 60% of its original volume.

      VOLCOT = WSHULL*(COT/12)
      VOLSURF = VOLHULL + VOLCOT
      VOLSUB = VOLHULL + 0.6*VOLCOT

      DISPSURF = VOLSURF/36.0
      DISPSUB = VOLSUB/36.0

      DISPCHANGE = DISPSURF - DISPSUB

C     Calculate the required trim tank size.  Assume the trim tank is
C         10% larger than the change in volume and uses 90% of the hull
C           volume.  (36 cubic ft/ton fw)

      VOLTRIM = 1.1 * DISPCHANGE * 36.0
      LTRIM = VOLTRIM / (0.9*(PI/4.0)*D**2)


C     Calculate the lengths of the forward and aft main ballast
C           assuming the forward MBT is 7% and the aft MBT is 5% of the
C            total LSV volume of (1% in each for tank for equipment).

      VOLMBTF = 0.0
      MOMMBTF      = 0.0
      I=0

500   IF (VOLMBTF .LT. (0.07*VOLSUB)) THEN
            I = I+1
            VOLMBTF = VOLMBTF+ (PI/4)*((RF(I)+RF(I+1))**2)*(XF(I+1)-XF(I))
            MOMMBTF = MOMMBTF+ (PI/4)*((RF(I)+RF(I+1))**2)*
     *                           (XF(I+1)-XF(I))*(XF(I+1)+XF(I))/2

            GOTO 500
      END IF

      LMBTF = LF * I / (DIVF-1)
      LCGMBTF = MOMMBTF/VOLMBTF

      VOLMBTA = 0.0
      MOMMBTA = 0.0
      I= DIVA

600   IF (VOLMBTA .LT. (0.05*VOLSUB))  THEN
            I = I-1
            VOLMBTA = VOLMBTA+(PI/4)*((RA(I)+RA(I+1))**2)*(XA(I+1)-XA(I))
            MOMMBTA = MOMMBTA + (PI/4)*((RA(I)+RA(I+1))**2)*
     *                           (XA(I+1)-XA(I))*(XA(I+1)+XA(I))/2
      GOTO 600

      END IF
      LMBTA = LA * (DIVA -I) / (DIVA-1)
      LCGMBTA = MOMMBTA/VOLMBTA
      LCGMBT = 0.6*LCGMBTF + 0.4*LCGMBTA

      RETURN
      END   SUBROUTINE CALC_GEOMETRY
```

```
C***********************************************************************
C  Subroutine CALC_WEIGHT determines the weight, vertical center of
C      gravity (VCG) and longitudinal center of LSV with the exception of
C      propulsor, hull coating and lead
C***********************************************************************


      SUBROUTINE CALC_WEIGHT (D,LD,LMBTF,LMBTA,BT,BP,COT,WSHULL,
     *                               A1WEIGHT, A1LCG, A1VCG, LBATT, WCOST)

      IMPLICIT NONE

      REAL D, LD, LMBTF, LMBTA, BP,COT, WSHULL, A1WEIGHT, A1LCG, A1VCG,
     * PI, L, W1, LCG1, VCG1, W2, LCG2, VCG2,
     * W3, LCG3, VCG3,
     * BATT_WT_SP_PWR(4), BATT_VOL_SP_PWR(4),
     * WBATT, VBATT, LBATT, LCGBATT, VCGBATT,
     * WCABLE, LCGCABLE, VCGCABLE,
     * W3OTHER, LCG3OTHER, VCG3OTHER,
     * W4, LCG4, VCG4, W5, LCG5, VCG5, WCOOLING, W5OTHER,
     * W6, LCG6, VCG6, W7, LCG7, VCG7,
     * W6OTHER , WCOT, LCG6OTHER, LCGCOT, VCG6OTHER, VCGCOT,
     * WCOST(7)

      INTEGER BT

C     BATT_VOL_SP_PWR - Battery specific power per unit volume
C     BATT_WT_SP_PWR - Battery specific power per unit weight
C     LCG* - Longitudinal center of gravity for group *
C     VCG* - Vertical center of gravity for group *
C     W* - Weight of group *

      PARAMETER (PI=3.1415926)

      L = D * LD

C     Weight Group 1 (Structures)
C            Weight - ratio with LSV A1 wetted surface area
C                   LSV A1 W1 = 59.0 tons
C                   LSV A1 WSHULL = 2920 sq ft
C`           LCG and LCV - use LSV A1 ratio to L and D
C
      W1 = (59.0/2920.0)*WSHULL
      LCG1 = (0.489) * L
      VCG1 = (0.487) * D

C     Weight Group 2 (Propulsion with exception of propulsor)
C            Weight - Same as LSV A1    (16.2 tons)
C            LCG - 9 ft. forward of aft pressure hull
C                   (Same location as LSV A1)
C            VCG - LSV A1 VCG/D ratio

      W2 = 16.2
      LCG2 = L - LMBTA - 9
      VCG2 = 0.5 * D

C     Weight Group 3 (Electric Plant)
C            Weight- Battery: Power divided by specific power per weight
C                     Cable: Distance from battery center to motor controller
C                                 multiplied by cable density from LSV A1.
C                         Other: Same as LSV A1 (2.3 tons)
C            LCG-   Battery: Assume battery uses 40% of available space and
C                                        starts 2 ft. aft of forward MBT.
C                   Cable: Half-way between battery center and motor C
C                          controller.
C                   Other: LSV A1 LCG/L ratio (0.45)
```

```
C           VCG -  LSV A1 VCG/D ratio: Battery (0.43)
C                                      Cable (0.55)
C                                      Other (0.45)
C           Battery volume- Power divided by specific power per volume.
C           Battery Length (LBATT)- Assume 20% of the hull can be used for
C                  battery. (65% for structures and spacing from LSV A1
C                  drawing 15% for cooling from GNB paper)

      BATT_WT_SP_PWR (1) = 45.2
      BATT_WT_SP_PWR (2) = 62.2
      BATT_WT_SP_PWR (3) = 106.6
      BATT_WT_SP_PWR (4) = 181.6

      BATT_VOL_SP_PWR (1) = 4.87
      BATT_VOL_SP_PWR (2) = 5.70
      BATT_VOL_SP_PWR (3) = 5.0
      BATT_VOL_SP_PWR (4) = 13.8

      WBATT = BP / BATT_WT_SP_PWR (BT)
      VBATT = BP / BATT_VOL_SP_PWR (BT)
      LBATT = ((VBATT)/0.2) / ((PI/4.0)*(D**2))
      LCGBATT = LMBTF + 2.0 + LBATT/2.0
      VCGBATT= (0.43)* D

      WCABLE = (5.0/(70.0-33.0)) *(L-LMBTA-22.0-LCGBATT)

      LCGCABLE = (L-LMBTA-2+LCGBATT) / 2.0
      VCGCABLE = (0.55) * D

      W3OTHER = 2.3
      LCG3OTHER = 0.45 * D
      VCG3OTHER = 0.5 * D

      W3 = WBATT + WCABLE + W3OTHER
      LCG3 = (WBATT*LCGBATT + WCABLE*LCGCABLE + W3OTHER*LCG3OTHER)/W3
      VCG3 = (WBATT*VCGBATT + WCABLE*VCGCABLE + W3OTHER*VCG3OTHER)/W3

C     Weight Group 4 (Command and Control)
C           Weight - Same as LSV A1 (6.5 tons)
C           LCG - 26 ft forward of aft MBT
C           VCG - LSV A1 VCG/D ratio (0.5)

      W4 = 6.5
      LCG4 = L- LMBTA - 26.0
      VCG4 = 0.5 * D

C     Weight Group 5 (Auxiliaries)
C           Weight-      Cooling: LSV A1 Weight/Battery Power ratio
C                               (2.5 tons, 2673 kw)
C                        Other: LSV A1 Weight/Length ratio
C                               (6.1 tons, 110 feet)
C           LCG- 26 feet forward of aft MBT
C           VCG- LSV A1 VCG/D ratio (0.5)

      WCOOLING = (2.5 / 2673.0) * BP
      W5OTHER = (6.1 / 110.0) * L
      W5 = WCOOLING + W5OTHER

      LCG5 = L - LMBTA - 26.0
      VCG5 = 0.5 * D

C     Weight Group 6 (Outfit and Furnishings)
C           Weight- Other: LSV A1 Weight/Length ratio
C                                      (2 tons, 110 feet)
C                        Hull Coating: 60 cubic feet / ton
C                               with uncompressed volume equal to
C                               wetted surface area multiplied by
```

```
C                                   coating thickness.
C            LCG-  Other: LSV A1 LCG/L ratio (0.62)
C                       Hull Coating: Same as LCG for W1
C            VCG- Other: LSV A1 VCG/D ratio (0.45)
C                     Hull Coating: Center line

      W6OTHER = (2.0 / 110.0) * L
      WCOT = WSHULL * (COT/12.0) / 60.0

      LCG6OTHER = 0.62 * L
      LCGCOT = 0.489 * L

      VCG6OTHER = 0.45 *D
      VCGCOT = 0.5 * D

      W6 = W6OTHER + WCOT

      LCG6 = (W6OTHER*LCG6OTHER + WCOT*LCGCOT) / W6
      VCG6 = (W6OTHER*VCG6OTHER + WCOT*VCGCOT) / W6

C     Weight Group 7 (Instrumentation)
C            Weight - LSV A1 Weight/Length ratio (2.23 tons, 110ft)
C            LCG - LSV A1 LCG/L ratio (0.53)
C            VCG - LSV A1 VCG/D ratio (0.5)

      W7 = (2.23/110.0) * L
      LCG7 = 0.53 * L
      VCG7 = 0.5 * D

C     Calculate total weight, LCG and VCG

      A1WEIGHT = W1 + W2 + W3 + W4 + W5 + W6 + W7
      A1LCG =  (W1*LCG1 + W2*LCG2 + W3*LCG3 + W4*LCG4 + W5*LCG5 +
     *       W6*LCG6 + W7*LCG7) / A1WEIGHT
      A1VCG =  (W1*VCG1 + W2*VCG2 + W3*VCG3 + W4*VCG4 + W5*VCG5 +
     *       W6*VCG6 + W7*VCG7) / A1WEIGHT

C     Assign weights to the array used in cost calculation

      WCOST(1) = W1
      WCOST(2) = WBATT
      WCOST(3) = W3OTHER
      WCOST(4) = WCOOLING
      WCOST(5) = W5OTHER
      WCOST(6) = WCOT
      WCOST(7) = W6OTHER


      END SUBROUTINE CALC_WEIGHT
```

```
      SUBROUTINE COST (MBR, WCOST, BALANCE_OUT, DTOC, ACQU_COST)

C*******************************************************************
C     Subroutine COST     calculates total ownership cost from battery
C           type, battery power and various weight groups.
C           Note: All costs are in thousands of FY97 dollars
C           Programmer:  Allan Andrew
C                 5/5/98
C*******************************************************************
      IMPLICIT NONE


      REAL  ACQU_COST,    BALANCE_OUT (7),
     *      BP,    BPCER, BPCOST,       CONSTANT_COST,      COT,
     *      COTCOST,      DF3_20,       DF5,   DF10,  DF15,
     *      DF20,  DF1_20,       DR,    DISPOSAL_COST,
     *      DTOC,  MBR(8),       SONARCOST,    UPGRD_COST,
     *      VOLCOT,       VOLCOTCER,    W1,    W1CER, W1COST,
     *      W3OTHER,      W3OTHERCER,   W3OTHERCOST,
     *      W5OTHER,      W5OTHERCER,   W5OTHERCOST,
     *      W6OTHER,      W6OTHERCER,   W6OTHERCOST,
     *      WCOOLING,     WCOOLINGCER,  WCOOLINGCOST,
     *      WCOST(7),
     *      WSCOT, WSCOTCER,
     *      YEARLY_COST

      INTEGER BT,   I,     SONAR

C     *CER - Cost estimating relationship for *
C           W*CER - $K/TON
C           BPCER - $K/kW
C           VOLCOTCER - $K/ft^3
C           WSCOTCER - $K/ft^2
C     CONSTANT_COST - Portion of acquisition cost that is the same for all
C           variants of LSV
C     DISPOSAL_COST -     Cost of disposal of LSV at end of life
C     DR - Discount rate used to calculate discounted total ownership cost
C     DF* - Discount factor for * years
C                 3_20 is DF for battery replacement every 3 years
C     UPGRD_COST - Discounted cost of upgrades for GNC and new batteries.
C     YEARLY_COST - Total discounted yearly costs of operating the LSV

      PARAMETER  (BPCER=0.746,   W1CER=76.0,   W3OTHERCER=171.0,
     *            W5OTHERCER=763.0,   W6OTHERCER=683.0,
     *            WCOOLINGCER=763.0,  VOLCOTCER=0.897,
     *            WSCOTCER=0.234,     DR = 0.06)

      BT = INT (MBR(5))
      BP = MBR(6)
      SONAR = INT (MBR(8))

      W1 = WCOST(1)
      W3OTHER = WCOST(3)
      WCOOLING = WCOST(4)
      W5OTHER = WCOST(5)
      W6OTHER = WCOST(7)

      WSCOT = BALANCE_OUT(6)
      COT = MBR(7)
      VOLCOT = WSCOT * COT / 12.0


C     Calculate discount factors for 5, 10, 15, 20 years and
C     a 20 year annuity

      DF3_20 = 1/((1+DR)**3) + 1/((1+DR)**6) + 1/((1+DR)**9) +
     *       1/((1+DR)**12) + 1/((1+DR)**15) + 1/((1+DR)**18)
```

```
      DF5 = 1/((1+DR)**5)
      DF10 =  1/((1+DR)**10)
      DF15 = 1/((1+DR)**15)
      DF20 = 1/((1+DR)**20)
      DF1_20 = 0
      I = 0

100   IF (I.LT.20) THEN
             I = I+1
             DF1_20 = DF1_20 + 1/((1+DR)**I)
             GOTO 100
      END IF

C     Determine cost of each portion of LSV by multiplying the SWBS weight
C     with the cost estimating relationship (CER)

      CONSTANT_COST = 28230.0
      W1COST = W1CER * W1
      W3OTHERCOST = W3OTHERCER * W3OTHER
      WCOOLINGCOST = WCOOLINGCER * WCOOLING
      W5OTHERCOST = W5OTHERCER * W5OTHER
      COTCOST = WSCOTCER * WSCOT + VOLCOTCER * VOLCOT
C     PRINT *, 'COTCOST = ', COTCOST
      W6OTHERCOST = W6OTHERCER * W6OTHER

      IF (BT.EQ.1)THEN
             BPCOST = BPCER * BP * 1.0
             UPGRD_COST = (1100.0 ) * (DF5 + DF10 + DF15)
     *                       + BPCOST * DF3_20
      ELSE IF (BT.EQ.2) THEN
             BPCOST = BPCER * BP * 1.0
             UPGRD_COST = 1100.0*(DF5 + DF10 + DF15) + BPCOST*DF1_20

      ELSE IF (BT.EQ.3) THEN
             BPCOST = BPCER * BP * 1.5
             UPGRD_COST = (1100.0 ) * (DF5 + DF10 + DF15)
     *                       + BPCOST * DF3_20

      ELSE IF (BT.EQ.4) THEN
             BPCOST = BPCER * BP * 2
             UPGRD_COST = (1100.0 ) * (DF5 + DF10 + DF15)
     *                       + BPCOST * DF3_20
      END IF

C     Calculate acquisition cost with 10% profit margin

      ACQU_COST =   (CONSTANT_COST + W1COST + W3OTHERCOST +
     *       WCOOLINGCOST + W5OTHERCOST + COTCOST + W6OTHERCOST +
     *       BPCOST)*1.1

C     Assume no additional cost if current sonar system is used.
C     Assume $3M dollar investment if sonar system is upgraded.
      IF (SONAR.EQ.1) THEN
             SONARCOST = 0
      ELSE IF (SONAR.EQ.2) THEN
             SONARCOST = 3000.0
      END IF

C     Assume yearly operating expenses of $7.17M.
      YEARLY_COST = DF1_20 * 7170.0
C     Assume disposal cost of $1M.
      DISPOSAL_COST = DF20 * 1000.0

      DTOC = ACQU_COST + SONARCOST + YEARLY_COST
     *       + DISPOSAL_COST + UPGRD_COST
      END SUBROUTINE COST
```

```
      SUBROUTINE CALC_HA_MOE (VMAX, HI_SPD_RUNS, MBR, HAMOE)

C*******************************************************************
C     Subroutine CALC_HA_MOE calculates the hydro-acoustic measures of
C     effectiveness for each member of the LSV population
C           Programmer:  Allan Andrew
C                 5/5/98
C*******************************************************************

      IMPLICIT NONE

      REAL   COT,   ERROR, HAMOE, MBR(8),       V2,    V3,    VMAX

      INTEGER HI_SPD_RUNS,       SON

C     ERROR - A measure of the expected maximum error in measurement of
C                 the LSV acoustic signature
C     V2 - The speed of the final high speed run
C     V3 - The speed to which it is desired to extrapolate the
C           acoustic data

      PARAMETER (V3 = 15.0)

      COT = MBR(7)
      SON = MBR(8)

C     Calculate the error band.

      ERROR = 1.0 / (SON * (COT+1.0))

C     PRINT *, 'ERROR = ', ERROR

      IF (HI_SPD_RUNS .LE. 1) THEN
            HAMOE = 10
      ELSE
            V2 = 18.5


            HAMOE = 2 * ERROR * (LOG10(SQRT(VMAX*V2)/V3)) /
     *                                (LOG10(SQRT(VMAX/V2)))

      END IF

      END SUBROUTINE CALC_HA_MOE
```

```
      SUBROUTINE CALC_HD_MOE (MBR, BALANCE_OUT, FR_SPD_RUNS, HDMOE, GEO)

C*********************************************************************
C     Subroutine CALC_HD_MOE calculates the hydrodynamic measures of
C     effectiveness for each member of the LSV population
C           Programmer:  Allan Andrew
C                 5/5/98
C*********************************************************************
      IMPLICIT NONE

      REAL   BALANCE_OUT(7),     HDMOE, DMOE1,
     *       DMOE2, LD,    MARGIN,       MBR(8),      MARGIN_HD,
     *       MARG1(7,4),  MARG2(6,3),  MARTH, MARGOAL,      NA,    NF

      INTEGER      FR_SPD_RUNS, FSRHD, FSRTH, FSRGOAL,
     *       GEO,   I,     J,     K,     L

C*****Variables*******************************************************
C
c     HDMOE - Total Hydrodynamic MOE
C     DMOE1 - Hydrodynamic MOE for FR_SPD_RUNS
C     DMOE2 - Hydrodynamic MOE for Geo-simmilitude
C     FR_SPD_RUNS - Number of times the member can complete the sonar course
C           at Froude scaled speed
C     FSRHD - Number of Froude speed runs used to calculate HD MOE
C     FSRTH - The threshold for minimum FR_SPD_RUNS
C     GEO - Integer that represents the geo-similitude of the member
C                 0=None  1=SSN-21          2=NSSN
C     I - Counter in MARG1 that represents Iso-Value line
C     J - Counter in MARG1 that represents FR_SPEED_RUNS
C     K - Counter in MARG2 that represents Iso-Value line
C     L - Counter in MARG1 that represents Geo-Similitude
C     MARGIN_HD - Margin used to calculate HD MOE
C     MARG1 - Array that contains the equivalent values of margin for changes
C           in number of Froude speed runs
C     MARG2 - Array that contains the equivalent values of margin for changes
C           in geo-similitude
C     MARGIN - Maximum weight that can be added at stern of member including
C           propulsor


C     Assign the values to MARG1 and MARG2 determined from MAIE survey.

        MARG1(1,1)=.03; MARG1(1,2)=0.0; MARG1(1,3)=0.0; MARG1(1,4)=0.0;
        MARG1(2,1)=.035; MARG1(2,2)=.03; MARG1(2,3)=0.0; MARG1(2,4)=0.0;
        MARG1(3,1)=.05; MARG1(3,2)=.04; MARG1(3,3)=.03; MARG1(3,4)=0.0;
        MARG1(4,1)=.06; MARG1(4,2)=.05; MARG1(4,3)=.04; MARG1(4,4)=.03;
        MARG1(5,1)=.09; MARG1(5,2)=.08; MARG1(5,3)=.07; MARG1(5,4)=.06;
        MARG1(6,1)=.12;MARG1(6,2)=.11;MARG1(6,3)=.10;MARG1(6,4)=.09;
        MARG1(7,4)=.12

      MARG1(7,3)=MARG1(7,4) + MARG1(6,3) - MARG1(6,4)
      MARG1(7,2)=MARG1(7,4) + MARG1(6,2) - MARG1(6,4)
      MARG1(7,1)=MARG1(7,4) + MARG1(6,1) - MARG1(6,4)

      MARG2(1,1)=.03; MARG2(1,2)=0.0; MARG2(1,3)=0.0
      MARG2(2,1)=.04; MARG2(2,2)=.03;  MARG2(2,3)=0.0
      MARG2(3,1)=.05; MARG2(3,2)=.04; MARG2(3,3)=.03
      MARG2(4,1)=.08; MARG2(4,2)=.07; MARG2(4,3)=.06
      MARG2(5,1)=.11; MARG2(5,2)=.10; MARG2(5,3)=.09
      MARG2(6,3)=.12
      MARG2(6,2)=MARG2(6,3) + MARG2(5,2) - MARG2(5,3)
      MARG2(6,1)=MARG2(6,3) + MARG2(5,1) - MARG2(5,3)


C     Assign the values for the MOPS
      MARGIN = BALANCE_OUT(3) / BALANCE_OUT(1)
```

```
C       Determine the GEOSIM hull form
        LD = MBR(2)
        NF = MBR(3)
        NA = MBR(4)

C       NSSN IF:
        IF ((LD .GE. 10.0) .AND. (LD .LE. 12.0) .AND.
      * (NF .GE. 2.25) .AND. (NF .LE. 2.75) .AND.
      * (NA .GE. 2.5) .AND. (NA .LE. 3.0)) THEN
                      GEO = 2

C       SSN-21 IF:
        ELSE IF ((LD .GE. 7.0) .AND. (LD .LE. 9.0) .AND.
      * (NF .GE. 2.5) .AND. (NF .LE. 3.0) .AND.
      * (NA .GE. 2.75) .AND. (NA .LE. 3.25)) THEN
                             GEO = 1

C       Otherwise no Geo-sim
        ELSE
                      GEO = 0
        END IF

C       Calculate Hydrodynamic MOE for Froude Speed Runs

C       Enter the goals and thresholds
        FSRTH = 7;    FSRGOAL = 10

        MARTH = .03;  MARGOAL = .12

C       If number of Froude speed runs or margin less than the threshold,
C              set the MOE for Froude speed runs to zero.
        IF ( (FR_SPD_RUNS .LT. FSRTH) .OR. (MARGIN .LT. MARTH) ) THEN
               HDMOE = 0.0
               GOTO 1000
        END IF

C       If number of Froude speed runs or margin greater than goal, reduce
C              its value to the goal.

        IF (FR_SPD_RUNS     .GT. FSRGOAL) THEN
                      FSRHD = FSRGOAL
               ELSE
                      FSRHD = FR_SPD_RUNS
        END IF

C      WRITE (99,*) 'FSRHD = ', FSRHD

        IF (MARGIN .GT. MARGOAL) THEN
                      MARGIN_HD = MARGOAL
               ELSE
                      MARGIN_HD = MARGIN
        END IF

C       WRITE (99,*) 'MARGIN_HD = ', MARGIN_HD

C       Set the value of J to enter MARG1 matrix.
        J = FSRHD - FSRTH + 1

C       Search the MARG1 matrix for the value of Froude speed runs and margin.
C              Interpolate and return the equivalent margin for threshold of
C              Froude speed runs.

        I = 1

100     IF ( MARGIN_HD .LE. MARG1(I+1,J) ) THEN
```

```
          DMOE1 = (MARGIN_HD - MARG1(I,J))*(MARG1(I+1,1) - MARG1(I,1))/
     *                    (MARG1(I+1,J) - MARG1(I,J))   +  MARG1(I,1)

          ELSE
                I = I+1
                GOTO 100
      END IF

C     WRITE (99,*) 'DMOE1 = ',DMOE1

C     Set the value of L to enter MARG2 matrix
      L = GEO + 1

C     Search the MARG2 matrix for the value of Froude speed runs and
C           Geo-similitude. Interpolate and return the CHANGE in equivalent
C           margin from threshold Geo-sim.

      K = 1


200   IF ( MARGIN_HD .LE. MARG1(K+1,L) ) THEN

          DMOE2=((MARGIN_HD - MARG2(K,L))*(MARG2(K+1,1) - MARG2(K,1))/
     *              (MARG2(K+1,L) - MARG2(K,L)) + MARG2(K,1)) -
     *              MARGIN_HD

          ELSE
                K = K+1
                GOTO 200
      END IF

      HDMOE = DMOE1 + DMOE2

1000  CONTINUE

7010  FORMAT (7(F9.2))
7020  FORMAT (6(F9.2))

      END SUBROUTINE CALC_HD_MOE
```

```
      SUBROUTINE   REPLACE (BIPOP, GENE, GENEL, POPLN, NUM_POP_CHAR,
     *                          GENSIZ, REPLACE_NUM, DTOC, HAMOE, HDMOE,
     *                          MBR, VARNUM, BALANCE_OUT, FR_SPD_RUNS,
     *                          HI_SPD_RUNS, VMAX,
     *                          GEO, ACQU_COST, GEN_NUM, GEN_NUM_MAX,
     *                          RUN_NUM, MBR_CHAR, VMAX_HA, SCALE)

C*****************************************************************************
C     Replace takes  member or child and inserts it into the population
C      and binary population arrays.
C
C       Programmer:  Allan Andrew 5/5/98
C******************************************************************************

      IMPLICIT NONE

      INTEGER FR_SPD_RUNS,       GENEL, GEN_NUM,
     *        GEN_NUM_HI,   GEN_NUM_LO,   GEN_NUM_MAX,
     *        GENSIZ,       BIPOP(GENEL,GENSIZ),
     *        GENE(GENEL),  HI_SPD_RUNS,
     *        I, J, GEO, NUM_POP_CHAR,
     *        REPLACE_NUM,  RUN_NUM,      VARNUM


      REAL   ACQU_COST, BALANCE_OUT(7),  DTOC,
     *        HAMOE, HDMOE,  MBR(VARNUM),       MBR_CHAR(NUM_POP_CHAR),
     *        PENALTY,      PENALTY_MAX,
     *        POPLN(NUM_POP_CHAR, GENSIZ), SCALE,
     *        VMAX, VMAX_HA

                     DO 200 I=1, GENEL
                            BIPOP(I, REPLACE_NUM) = GENE(I)
200                  CONTINUE

                     DO 210 J=4, VARNUM+3
                       POPLN(J,REPLACE_NUM) = MBR(J-3)
 210                 CONTINUE

                     POPLN(12,REPLACE_NUM) = BALANCE_OUT(1)
                     POPLN(13,REPLACE_NUM) = BALANCE_OUT(3)
                     POPLN(14,REPLACE_NUM) = BALANCE_OUT(4)
                     POPLN(15,REPLACE_NUM) = BALANCE_OUT(5)
                     POPLN(16,REPLACE_NUM) = FR_SPD_RUNS
                     POPLN(17,REPLACE_NUM) = HI_SPD_RUNS
                     POPLN(18,REPLACE_NUM) = VMAX
                     POPLN(19,REPLACE_NUM) = GEO
                     POPLN(20,REPLACE_NUM) = ACQU_COST/1000
                     POPLN(21,REPLACE_NUM) = GEN_NUM

                     POPLN(22,REPLACE_NUM) = DTOC/1000
                     POPLN(23,REPLACE_NUM) = HAMOE
                     POPLN(24,REPLACE_NUM) = -HDMOE
                     POPLN(25,REPLACE_NUM) = RUN_NUM
                     POPLN(26,REPLACE_NUM) = VMAX_HA
                     POPLN(27,REPLACE_NUM) = SCALE



      GEN_NUM_LO = NINT(0.2*GEN_NUM_MAX)
      GEN_NUM_HI = NINT(0.8*GEN_NUM_MAX)

      PENALTY_MAX = 10

      IF (GEN_NUM .LT. GEN_NUM_LO) THEN
             PENALTY = 1.0

      ELSE IF ((GEN_NUM .GE. GEN_NUM_LO) .AND.
```

```
*         (GEN_NUM .LE. GEN_NUM_HI)) THEN
        PENALTY = 10 ** ((LOG10(PENALTY_MAX)) * (GEN_NUM - GEN_NUM_LO)/
*                                  (GEN_NUM_HI - GEN_NUM_LO))

 ELSE
        PENALTY = 10**6

 END IF

 IF ( (POPLN(14,REPLACE_NUM) .EQ. 1.0) .OR.
*      (POPLN(15,REPLACE_NUM) .EQ. 1.0) ) THEN

        POPLN(1,REPLACE_NUM) = NINT ((DTOC/1000) * PENALTY)
        POPLN(2,REPLACE_NUM) = (FLOAT(NINT(1000*HAMOE * PENALTY)))/1000
        POPLN(3,REPLACE_NUM)=-(FLOAT(NINT(1000*HDMOE / PENALTY)))/1000

 ELSE
        POPLN(1,REPLACE_NUM) = NINT(DTOC/1000)
        POPLN(2,REPLACE_NUM) = (FLOAT(NINT(1000*HAMOE)))/1000
        POPLN(3,REPLACE_NUM) = -(FLOAT(NINT(1000*HDMOE)))/1000
 END IF

 DO I=1, NUM_POP_CHAR
        MBR_CHAR(I) = POPLN(I,REPLACE_NUM)
 END DO


END SUBROUTINE REPLACE
```

```
      SUBROUTINE NON_DOMINATED (MBR_CHAR, NUM_POP_CHAR,
     *                              NON_DOM, NUM_NON_DOM_MAX, NUM_NON_DOM,
     *                              ADD_TNUM, REMOVE_TNUM, EXH_SEARCH)


C***********************************************************************
C     Subroutine NON_DOMINATED stores all members that are on the non-
C           dominated frontier.
C       Programmer:  Allan Andrew 5/5/98
C************************************************************************

      IMPLICIT NONE


      INTEGER      ADD_TNUM,     COUNTER,      I,     J,
     *      NUMBER_FOUND, NUM_NON_DOM,  NUM_NON_DOM_MAX,
     *      NUM_POP_CHAR, NUM_REMOVE,   REMOVE_TNUM


      REAL NON_DOM (NUM_POP_CHAR, NUM_NON_DOM_MAX),
     *      EXH_SEARCH(3, 184), PENALTY,
     *      MBR_CHAR (NUM_POP_CHAR)

      INTEGER REMOVE(NUM_NON_DOM_MAX)

      LOGICAL CLONE,      NEW_MBR,      NON_DOM_MBR, ND_MBR_ADDED,
     *      ND_MBR_FOUND

C     ADD - An array that stores the location of the members of the POPLN
C           array that are to be added to the Non-Dom array
C     CLONE - Logical variable to determine if member is clone of non-dom
C     COUNTER - Counts the number of times the subroutine has been called
C     NEW_MBR - Logical variable to determine if a member with the same
C                 MOE's and cost is different type
C     NUM_ADD - The number of members from the population array that are to
C                 be added to the Non-Dom array.
C     NON_DOM - The array that holds the characteristics of the don-dominated
C                 individuals
C     NON_DOM_MBR - A logical variable that is true if the member of the
C                       population is non-dominated and false if dominated.
C     NUM_NON_DOM - The number of non-dominated individuals
C     NUM_REMOVE - The number of individuals to be removed from the Non-Dom
C                 array
C     PENALTY - The max penalty applied if the variant is too long or too
C                 heavy
C     PREVIOUSLY_REMOVED - Logical variable that determines if a member has
C                 been already been marked for removal from the population
C     REMOVE - An array that stores the location of the members of the Non-
C                 Dom array that are to be removed because they are
C                 dominated by new individuals



      ND_MBR_ADDED = .FALSE.
      COUNTER = COUNTER + 1

C     Apply the maximum penalty to the MOE's and cost if the variant is
C           infeasible.

            IF ( (MBR_CHAR(14) .EQ. 1.0).OR.(MBR_CHAR(15) .EQ. 1.0)
     *            .OR. (MBR_CHAR(17) .LE. 1)) THEN
                  MBR_CHAR(1) = 100000000
                  MBR_CHAR(2) = 100000000
                  MBR_CHAR(3) = 100000000
            END IF

C     If there are no members in the non-dominated array,  place the
```

```
C       the member in the non-dom array.

        IF (NUM_NON_DOM     .EQ. 0) THEN

               NUM_NON_DOM = NUM_NON_DOM + 1
               ADD_TNUM = ADD_TNUM + 1
               ND_MBR_ADDED = .TRUE.

               DO J=1, NUM_POP_CHAR
                      NON_DOM(J,NUM_NON_DOM) = MBR_CHAR(J)
               END DO

C       If there are already members in the non-dominated array, compare
C       the member to determine if it should be inserted and which
C        members should be removed from the non-dominated array.

        ELSE

        NUM_REMOVE = 0

                      IF        (    (MBR_CHAR(1) .GE. NON_DOM(1,J))
     *           .AND.         (MBR_CHAR(2) .GE. NON_DOM(2,J))
     *           .AND.         (MBR_CHAR(3) .GE. NON_DOM(3,J)) ) THEN
                                     NON_DOM_MBR = .FALSE.
                      END IF
200            CONTINUE

               IF (NON_DOM_MBR) THEN
                      DO 300 J=1, NUM_NON_DOM
                             IF        (     (MBR_CHAR(1) .LE. NON_DOM(1,J))
     *                       .AND.  (MBR_CHAR(2) .LE. NON_DOM(2,J))
     *                       .AND.  (MBR_CHAR(3) .LE. NON_DOM(3,J)) ) THE
                                           NUM_REMOVE = NUM_REMOVE + 1
                                           REMOVE (NUM_REMOVE) = J
                             END IF
300                   CONTINUE

                      IF (NUM_REMOVE .EQ. 1) THEN
                             DO J=1, NUM_POP_CHAR
                                    NON_DOM(J, REMOVE(1)) = MBR_CHAR(J)
                             END DO
                      ELSE IF (NUM_REMOVE .GT. 1) THEN
                             DO J=1, NUM_POP_CHAR
                                    NON_DOM(J, REMOVE(1)) = MBR_CHAR(J)
                             END DO
                             DO I = 2, NUM_REMOVE
                                    DO J=1, NUM_POP_CHAR
                                           NON_DOM(J, REMOVE(I)) =
     *                                     NON_DOM(J, NUM_NON_DOM - I + 2)
                                    END DO
                             END DO
                      ELSE IF (NUM_REMOVE .EQ. 0) THEN
                             DO J=1, NUM_POP_CHAR
                                    NON_DOM(J, NUM_NON_DOM + 1) = MBR_CHAR (J)
                             END DO
                      END IF

                      NUM_NON_DOM = NUM_NON_DOM + 1 - NUM_REMOVE
                      ADD_TNUM = ADD_TNUM + 1
                      ND_MBR_ADDED = .TRUE.
                      REMOVE_TNUM = REMOVE_TNUM + NUM_REMOVE

               ELSE
                      CLONE = .FALSE.
                      NEW_MBR = .FALSE.
                      DO 1000 J=1, NUM_NON_DOM
                             IF        (     (MBR_CHAR(1) .EQ. NON_DOM(1,J))
```

```
     *                  .AND.       (MBR_CHAR(2) .EQ. NON_DOM(2,J))
     *                  .AND.       (MBR_CHAR(3) .EQ. NON_DOM(3,J)) ) THEN

                                    IF       (    (MBR_CHAR(4) .EQ. NON_DOM(4,J))
     *                        .AND. (MBR_CHAR(5) .EQ. NON_DOM(5,J))
     *                        .AND. (MBR_CHAR(6) .EQ. NON_DOM(6,J))
     *                        .AND. (MBR_CHAR(7) .EQ. NON_DOM(7,J))
     *                        .AND. (MBR_CHAR(8) .EQ. NON_DOM(8,J))
     *                        .AND. (MBR_CHAR(9) .EQ. NON_DOM(9,J))
     *                        .AND. (MBR_CHAR(10) .EQ. NON_DOM(10,J))
     *                        .AND. (MBR_CHAR(11) .EQ. NON_DOM(11,J)) ) THEN

                                                 CLONE = .TRUE.

                                    ELSE
                                                 NEW_MBR = .TRUE.

                                    END IF
                             END IF
1000                  CONTINUE

                      IF ((NEW_MBR) .AND. (.NOT. CLONE)) THEN

                             DO J=1, NUM_POP_CHAR
                                    NON_DOM(J, NUM_NON_DOM + 1) = MBR_CHAR (J)
                             END DO

                             NUM_NON_DOM = NUM_NON_DOM + 1
                             ADD_TNUM = ADD_TNUM + 1
                             ND_MBR_ADDED = .TRUE.
                      END IF

               END IF

        END IF

        ND_MBR_FOUND = .FALSE.
        IF (ND_MBR_ADDED) THEN
        DO I=1, 326
               IF (      (MBR_CHAR(1) .EQ. EXH_SEARCH(1,I))
     *         .AND. (MBR_CHAR(2) .EQ. EXH_SEARCH(2,I))
     *         .AND. (MBR_CHAR(3) .EQ. EXH_SEARCH(3,I)) ) THEN
                      ND_MBR_FOUND = .TRUE.
               END IF
        END DO

               IF (ND_MBR_FOUND) THEN
                      NUMBER_FOUND = NUMBER_FOUND + 1
                      WRITE (72,*) NUMBER_FOUND, COUNTER
                      print *, 'NBR FOUND/COUNTER',NUMBER_FOUND, COUNTER
               END IF

        END IF

C       WRITE (32, *) NUM_ADD, NUM_REMOVE, NUM_NON_DOM

 7020 FORMAT (25(F10.3))

        RETURN
        END SUBROUTINE NON_DOMINATED
```

```
      SUBROUTINE TOURNAMENT (POPLN, NUM_POP_CHAR, GENSIZ,
     *                                  IDUM, PARENT, KILL)

C***************************************************************************
C     Subroutine TOURNAMENT takes the population array and selects
C      2 members for parents and 2 members for removal.
C
C     Programmer:  Allan Andrew  5/5/98
C***************************************************************************
      IMPLICIT NONE


      INTEGER       GENSIZ,       COUNT, DOMARR(GENSIZ,GENSIZ),     HI_NICHE,
     *        I,      IDUM,  J,     KILL(2),      LEAST, LOC_HI_NICHE(GENSIZ),
     *        LOC_LOW_NICHE(GENSIZ),     LOSER(GENSIZ),
     *        LOSSES,       LOW_NICHE,     MOST, NICHE_COUNT(GENSIZ),
     *        NUM_HI_NICHE, NUM_LOW_NICHE,       NUM_POP_CHAR,
     *        PARENT(2),    TNUM,
     *        TSIZE, TVEC(GENSIZ), WINNER(GENSIZ),     WINS


      REAL    POPLN(NUM_POP_CHAR,GENSIZ),        RAN2

C     COUNT - A count of the number of other members that dominate an
C                   individual
C     DOMARR - Represents the dominance of members of the population array
C            with respect to other members.
C                   If "I" dominates "J", then
C                          DOMARR(I,J) = +1
C                          DOMARR(J,I) = -1
C                   If neither member dominates, then
C                          DOMARR(I,J) = 0
C     LOSER - The numbers of the members that loose the tournament
C     LOSSES - The number of members that loose the tournament
C     TNUM - The number of the tournament (1 or 2)
C     TSIZE - Tournament size
C     WINNER - The numbers of the members that win the tournament
C     WINS - The number of members that win the tournament

C     Calculate how many individuals are "close" to each individual in
C            effectiveness/cost space.

      CALL NICHE (POPLN, NUM_POP_CHAR, GENSIZ, NICHE_COUNT)

C     Choose the tournament size to be a fraction of the generation size
      TSIZE = NINT (0.1*GENSIZ)

C     Randomly select tournament contestants.

      TNUM=1

50           DO I=1, TSIZE
100                 TVEC(I) = INT(ran2(IDUM) * FLOAT(GENSIZ-1)) + 1

C                   Prevent duplicate selections
                    DO J=1, I-1
                          IF (TVEC(J) .EQ. TVEC(I)) GOTO 100
                    END DO
             END DO

C            Zero the dominance array and winner/loser vectors
             DO I = 1,GENSIZ
               WINNER(I) = 0
               LOSER(I) = 0
               DO J = 1,GENSIZ
                  DOMARR(I,J) = 0
               END DO
```

```
            END DO

C           Construct the dominance array using only the tournament
C           contestants.

            DO I = 1,TSIZE-1
           DO J = I+1,TSIZE
              IF((POPLN(1, TVEC(I)) .GT. POPLN(1, TVEC(J)).AND.
     *            POPLN(2, TVEC(I)) .GE. POPLN(2, TVEC(J)).AND.
     *            POPLN(3, TVEC(I)) .GE. POPLN(3, TVEC(J)))
     *                  .OR.
     *           (POPLN(1, TVEC(I)) .GE. POPLN(1, TVEC(J)).AND.
     *            POPLN(2, TVEC(I)) .GT. POPLN(2, TVEC(J)).AND.
     *            POPLN(3, TVEC(I)) .GE. POPLN(3, TVEC(J)))
     *                  .OR.
     *           (POPLN(1, TVEC(I)) .GE. POPLN(1, TVEC(J)).AND.
     *            POPLN(2, TVEC(I)) .GE. POPLN(2, TVEC(J)).AND.
     *            POPLN(3, TVEC(I)) .GT. POPLN(3, TVEC(J))))THEN
                  DOMARR(I,J) = -1
                  DOMARR(J,I) = +1
         ELSE IF((POPLN(1, TVEC(I)) .LT. POPLN(1, TVEC(J)).AND.
     *            POPLN(2, TVEC(I)) .LE. POPLN(2, TVEC(J)).AND.
     *            POPLN(3, TVEC(I)) .LE. POPLN(3, TVEC(J)))
     *                  .OR.
     *           (POPLN(1, TVEC(I)) .LE. POPLN(1, TVEC(J)).AND.
     *            POPLN(2, TVEC(I)) .LT. POPLN(2, TVEC(J)).AND.
     *            POPLN(3, TVEC(I)) .LE. POPLN(3, TVEC(J)))
     *                  .OR.
     *           (POPLN(1, TVEC(I)) .LE. POPLN(1, TVEC(J)).AND.
     *            POPLN(2, TVEC(I)) .LE. POPLN(2, TVEC(J)).AND.
     *            POPLN(3, TVEC(I)) .LT. POPLN(3, TVEC(J))))THEN
                  DOMARR(I,J) = +1
                  DOMARR(J,I) = -1
              END IF
           END DO
            END DO

C      Find the least and most dominated individual(s) in this tournament
C     by finding the row(s) with the fewest and most -1's respectively.
C     In the first tournament, all members compete against each other
C     for selection as the first parent and the first lethal.

            LEAST  = 9999
            MOST   = 0
            WINS   = 0
            LOSSES = 0

            DO 400 I = 1,TSIZE

C           Count the members who dominate this individual
                   COUNT = 0
                   DO J = 1,TSIZE
                          IF (DOMARR(I,J) .EQ. -1) COUNT = COUNT + 1
                   END DO

C           Update the least dominated individual(s) found so far
        IF (COUNT .LT. LEAST) THEN
           LEAST = COUNT
           WINS = 1
           WINNER(1) = TVEC(I)

        ELSE IF (COUNT .EQ. LEAST) THEN
           WINS = WINS + 1
           WINNER(WINS) = TVEC(I)
        END IF
```

```
C           Update the most dominated individual(s) found so far
         IF (COUNT .GT. MOST) THEN
            MOST = COUNT
            LOSSES = 1
            LOSER(1) = TVEC(I)

         ELSE IF (COUNT .EQ. MOST) THEN
            LOSSES = LOSSES + 1
            LOSER(LOSSES) = TVEC(I)
         END IF
 400  CONTINUE

C           If only one winner, choose it as a parent.  If more than one
C           winner, choose the one with the lowest niche count.  If more
C           than one ties for lowest niche count, the parent is chosen
C           randomly.

            IF (WINS .EQ. 1) THEN
                  PARENT(TNUM) = WINNER(1)

            ELSE
                  LOW_NICHE = GENSIZ
                  NUM_LOW_NICHE = 0
                  DO 500 I=1, WINS
                        IF (NICHE_COUNT(WINNER(I)) .LT. LOW_NICHE) THEN
                              LOW_NICHE = NICHE_COUNT(WINNER(I))
                              NUM_LOW_NICHE = 1
                              LOC_LOW_NICHE(NUM_LOW_NICHE) = WINNER(I)

                        ELSE IF (NICHE_COUNT(WINNER(I)) .EQ. LOW_NICHE) THEN
                              NUM_LOW_NICHE = NUM_LOW_NICHE + 1
                              LOC_LOW_NICHE(NUM_LOW_NICHE) = WINNER(I)
                 ENDIF
500               CONTINUE
                  IF (NUM_LOW_NICHE .EQ. 1) THEN
                        PARENT(TNUM) = LOC_LOW_NICHE(1)
                  ELSE
                        PARENT(TNUM) = LOC_LOW_NICHE
    *                                 (INT(ran2(IDUM)*FLOAT(NUM_LOW_NICHE-
1))+1)
                  END IF
C      PRINT *, 'NUM_LOW_NICHE = ', NUM_LOW_NICHE
            END IF


C           If only one LOSER, choose it as a LETHAL.  If more than one
C           LOSER, randomly choose one as a LETHAL.

            IF (LOSSES .EQ. 1) THEN
                  KILL(TNUM) = LOSER(1)
            ELSE
                  HI_NICHE = 0
                  NUM_HI_NICHE = 0
                  DO 600 I=1, LOSSES
                        IF (NICHE_COUNT(LOSER(I)) .GT. HI_NICHE) THEN
                              HI_NICHE = NICHE_COUNT(LOSER(I))
                              NUM_HI_NICHE = 1
                              LOC_HI_NICHE(NUM_HI_NICHE) = LOSER(I)

                        ELSE IF (NICHE_COUNT(LOSER(I)) .EQ. HI_NICHE) THEN
                              NUM_HI_NICHE = NUM_HI_NICHE + 1
                              LOC_HI_NICHE(NUM_HI_NICHE) = LOSER(I)
                 ENDIF
600               CONTINUE
                  IF (NUM_HI_NICHE .EQ. 1) THEN
                        KILL(TNUM) = LOC_HI_NICHE(1)
                  ELSE
```

```
                    KILL(TNUM) = LOC_HI_NICHE *
     *                     (INT(ran2(IDUM)*FLOAT(NUM_HI_NICHE-1))+1)
                 END IF

           END IF

C          If only first tournament has been completed, increment tournament
C                 number and repeat.

           IF (TNUM .EQ. 1) THEN
                 TNUM = 2
                 GOTO 50
           END IF

C          Prevent duplicate parents and lethals.

           IF ((KILL(1) .EQ. KILL(2)) .OR. (PARENT(1) .EQ. PARENT(2)))
     *     THEN
                 GOTO 50
           END IF

      RETURN
      END SUBROUTINE TOURNAMENT
```

```
      SUBROUTINE NICHE (POPLN, NUM_POP_CHAR, GENSIZ,
     *                                   NICHE_COUNT)

C*****************************************************************************
C     Subroutine NICHE determines how many members of the population are
C           near each member of the population.
C       Programmer:  Allan Andrew 5/5/98
C*****************************************************************************

      IMPLICIT NONE

      INTEGER      GENSIZ,       I,     J,     NCLOSE,      NUM_POP_CHAR,
     *       NICHE_COUNT (GENSIZ)

      REAL   DEL_DTOC,     DEL_HAMOE,    DEL_HDMOE,
     *       DTOC_TOL,     HAMOE_TOL,    HDMOE_TOL,
     *       POPLN(NUM_POP_CHAR, GENSIZ)

C       *TOL - The tolerance associated with *
C      DEL* - Euclidean distance between points of *
C      NCLOSE - Crowding counter
C      NICHE_COUNT - A vector that contains the number of members that are
C             close to each individual in the population.

      DTOC_TOL = 4.0
      HAMOE_TOL = 0.3
      HDMOE_TOL = 0.03

C     Initialize the Niche_count vector.

      DO I=1, GENSIZ
             NICHE_COUNT (I) = 0
      END DO

      DO 200 I = 1,GENSIZ

C     Reset the crowding counter
        NCLOSE = 0

C     Find Euclidean distances to all other members of population
             DO 100 J = 1,GENSIZ

                    IF (J .NE. I) THEN

                           DEL_DTOC = ABS(POPLN(1,I) - POPLN(1,J))
                           DEL_HAMOE = ABS(POPLN(2,I) - POPLN(2,J))
                           DEL_HDMOE = ABS(POPLN(3,I) - POPLN(3,J))

                           IF (     (DEL_DTOC .LE. DTOC_TOL)
     *                      .AND.(DEL_HAMOE .LE. HAMOE_TOL)
     *                     .AND.(DEL_HDMOE .LE. HDMOE_TOL) )
     *                     THEN
                                  NCLOSE = NCLOSE + 1
                           END IF
                    END IF
100          CONTINUE

             NICHE_COUNT(I) = NCLOSE

200   CONTINUE

      RETURN
      END SUBROUTINE NICHE
```

```
      SUBROUTINE MATE (PARENT, BIPOP, GENEL, GENSIZ,
     *                     GEN_NUM, GEN_NUM_MAX, IDUM,
     *                     BI_CHILD1, BI_CHILD2)

C***********************************************************************
C     MATE takes two members of the population that have been designated
C            as parents.  It mates these two members by randomly breaking and
C            swapping their gene strings.  It then generates random mutations
C            and returns the children to the main program.
C
C       Programmer:  Allan Andrew 5/5/98
C***********************************************************************
      IMPLICIT NONE

      INTEGER      BREAK, GENEL, GEN_NUM,     GEN_NUM_MAX,
     *             GENSIZ,             I,     IDUM,  J

      INTEGER BI_CHILD1(GENEL),  BI_CHILD2(GENEL),
     *       BIPOP (GENEL,GENSIZ),      PARENT(2)

      REAL  MUTRAT, MUTRAT_HI,  MUTRAT_LO,    ran2

      LOGICAL CLONE1, CLONE2

C     BREAK - The randomly generated point at which the gene string is
C                 broken.
C     MUTRAT - The probability that any given chromosome will undergo
C                   mutation.
C     MUTRAT_HI - The mutation rate used in the first generation.
C     MUTRAT_LO - The mutation rate used in the last generation.


C     Mutation Rate (MUTRAT) is MUTRAT_HI for the first generation to
C           mate and reduces to MUTRAT_LO for the last generation.

      MUTRAT_HI = .1
      MUTRAT_LO = .01

c     MUTRAT = 10**( (LOG10(MUTRAT_LO) - LOG10(MUTRAT_HI))*(GEN_NUM-2)/
c    *                          (GEN_NUM_MAX-2  + LOG10(MUTRAT_HI) )
      mutrat = .01
C      PRINT *, 'MUTRAT = ', MUTRAT

C     Randomly select the point at which to break the gene string.

100   BREAK = INT( ran2(IDUM) * FLOAT(GENEL-2) ) + 1

C     PRINT *, 'BREAK = ', BREAK

C     Mate the two parents by crossover to generate two children.

      DO  I=1, BREAK

             BI_CHILD1(I) = BIPOP(I,PARENT(1))
             BI_CHILD2(I) = BIPOP(I,PARENT(2))

      END DO

      DO I = BREAK+1, GENEL
             BI_CHILD1(I) = BIPOP(I,PARENT(2))
             BI_CHILD2(I) = BIPOP(I,PARENT(1))
      END DO

C     Randomly mutate the gene

      DO I=1, GENEL
```

```
            IF (ran2(IDUM) .LT. MUTRAT) THEN
C       PRINT *, 'MUTATE CHILD1 AT I = ', I
                  IF (BI_CHILD1(I) .EQ. 0) THEN
                        BI_CHILD1(I) = 1
                  ELSE
                        BI_CHILD1(I) = 0
                  END IF
            END IF

            IF (ran2(IDUM) .LT. MUTRAT) THEN
C       PRINT *, 'MUTATE CHILD2 AT I = ', I

                  IF (BI_CHILD2(I) .EQ. 0) THEN
                        BI_CHILD2(I) = 1
                  ELSE
                        BI_CHILD2(I) = 0
                  END IF
            END IF

      END DO


      DO I=1, GENSIZ
            CLONE1 = .TRUE.

            DO J=1, GENEL
                  IF (BI_CHILD1(J) .NE. BIPOP(J,I)) THEN
                        CLONE1 = .FALSE.
                  END IF
                  IF (BI_CHILD2(J) .NE. BIPOP(J,I)) THEN
                        CLONE2 = .FALSE.
                  END IF

            END DO

            IF (CLONE1 .OR. CLONE2) THEN
C                 PRINT *, 'CLONE REJECTED'
                  GOTO 100
            END IF

      END DO

      END SUBROUTINE MATE
```

```
      SUBROUTINE ADJUST_MOES (POPLN, NUM_POP_CHAR, GENSIZ,
     *                                GEN_NUM, GEN_NUM_MAX)

C*****************************************************************************
C     ADJUST_MOES changes the cost and MOE's so that infeasible solutions
C           are penalized.  There is no penalty in the first 20% of the
C           generations and the penalty is increased over the next 60% of the
C           generations.  The final 20% of the generations have extreme
C           penalties to ensure that all feasible designs dominate the
C           infeasible design.
C       Programmer:  Allan Andrew 3/5/98
C*****************************************************************************

      IMPLICIT NONE

      INTEGER      GEN_NUM,      GEN_NUM_HI,  GEN_NUM_LO,   GEN_NUM_MAX,
     *       GENSIZ,       I,     NUM_POP_CHAR

      REAL  PENALTY_MAX,  PENALTY,      POPLN (NUM_POP_CHAR, GENSIZ)

C     GEN_NUM_HI - The generation number at which the penalty is maximum
C     GEN_NUM_LO - The generation number at which the penalty starts
C     PENALTY - The factor that is applied to change the value of MOE's
C                  for infeasible designs.
C     PENALTY_MAX - The value of the penalty at GEN_NUM_HI

      GEN_NUM_LO = NINT(0.2*GEN_NUM_MAX)
      GEN_NUM_HI = NINT(0.8*GEN_NUM_MAX)

      PENALTY_MAX = 10

c     IF (GEN_NUM .LT. GEN_NUM_LO) THEN
c           PENALTY = 1.0

c     ELSE IF ((GEN_NUM .GE. GEN_NUM_LO) .AND.
c    *               (GEN_NUM .LE. GEN_NUM_HI)) THEN
c           PENALTY = 10 ** ((LOG10(PENALTY_MAX)) * (GEN_NUM - GEN_NUM_LO)/
c    *                                      (GEN_NUM_HI - GEN_NUM_LO))

c     ELSE
            PENALTY = 10**6
c     END IF

C     PRINT * ,'PENALTY = ', PENALTY

      DO I=1, GENSIZ
            IF ( (POPLN(14,I) .EQ. 1.0) .OR. (POPLN(15,I) .EQ. 1.0) ) THEN
                  POPLN(1,I) = POPLN(22,I) * PENALTY
                  POPLN(2,I) = POPLN(23,I) * PENALTY
                  POPLN(3,I) = POPLN(24,I) / PENALTY
            END IF
      END DO

      END SUBROUTINE ADJUST_MOES
```

```
      PROGRAM FORMAT_DATA

C*************************************************************************
C     FORMAT_DATA takes the output of the non-dominated array and formats
C            it for plotting with excel.
C       Programmer:  Allan Andrew 5/5/98
C**************************************************************************

      IMPLICIT NONE

      INTEGER I,    J,     L,     M,     NUM_NON_DOM, NUM_NON_DOM_MAX,
     *              NUM_POP_CHAR, NUM_COST,    NUM_HD

      PARAMETER (NUM_POP_CHAR=27,       NUM_NON_DOM_MAX = 25000)

      REAL   NON_DOM (NUM_POP_CHAR,     NUM_NON_DOM_MAX),
     *       PLOT_ARRAY (100, 500),     MIN_COST,    MAX_COST,     MIN_HD

      OPEN (UNIT=41, FILE='NON_DOM2.OUT', STATUS='OLD')
      OPEN (UNIT=61, FILE='PLOT_ARR.OUT', STATUS='NEW')
      READ (41, *) NUM_NON_DOM

      DO I=1, NUM_NON_DOM
             READ (41, 7020) (NON_DOM (J,I),J=1,NUM_POP_CHAR)
      END DO

      MIN_COST = 100000
      MAX_COST = -100000
      MIN_HD = 100000

      DO 500 I=1, NUM_NON_DOM
             IF (NON_DOM(1,I) .LT. MIN_COST) THEN
                    MIN_COST = NON_DOM(1,I)
             END IF
             IF (NON_DOM(1,I) .GT. MAX_COST)    THEN
                    MAX_COST = NON_DOM(1,I)
             END IF
             IF (NON_DOM(3,I) .LT. MIN_HD) THEN
                    MIN_HD = NON_DOM(3,I)
             END IF
500   CONTINUE

      NUM_COST = MAX_COST - MIN_COST + 1
      NUM_HD = NINT(1000*(-MIN_HD)) + 1

      DO 1000 I=1, NUM_NON_DOM
             L = NINT(1000*(-NON_DOM(3,I))) + 2
             M = NINT(NON_DOM(1,I) - MIN_COST)+ 2
             PLOT_ARRAY(M,L) = NON_DOM(2,I)
1000  CONTINUE

      DO I=2, NUM_HD+1
             PLOT_ARRAY(1,I) = -.001*(I-2)
      END DO

     DO I=2,NUM_COST+1
             PLOT_ARRAY(I,1) = I + MIN_COST - 2
      END DO

      DO I=1, NUM_HD+1
             WRITE (61, 7050) (PLOT_ARRAY (J, I),J=1,NUM_COST+1)
      END DO

 7020 FORMAT (34(F10.3))
 7050 FORMAT (101(F10.3))

      END PROGRAM FORMAT_DATA
```

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